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Technical Memorandum

Further Development and Testing of the Sudbury Wind Diesel Hybrid Power Plant

DAF Indal Ltd.

March 1985

Canada

NRCC No. 27329

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Further Development and Testing of the Sudbury Wind Diesel Hybrid Power Plant

FINAL REPORT

March 4, 1985

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Canadian Perspectives on Wind-diesel Technology

Recent wind power development in Canada began with the re-invention of the Darrieus vertical axis wind turbine by the National Research Council of Canada (NRC) in the mid 1960's. As a result of NRC's Wind Energy R&D Program, vertical axis wind turbines (VAWT's) ranging in size originally from 1kW, presently from 50 kW to 4 MW, have been developed by Canadian companies.

In the late 1970's, the Ontario government and NRC cooperated in a small prototype wind-diesel hybrid generating system test on Toronto Island. The project was successful in demonstrating the feasibility of wind-diesel coupling and suggested that mechanical coupling could be made simpler and more efficient than electrical paralleling of a wind generator and diesel generator.

In 1980, a commercial scale 100 kW mechanically coupled wind-diesel system was tested in Sudbury, Ontario. The system comprised a 35 kW VAWT mechanically coupled to one of a pair of 50 kW diesel generators linked by an autosynchronizer. Computer controlled resistor banks simulated a time-variant community load, and a "dump" resistive load absorbed excess wind generated power in periods of low demand. The project was supported by Energy, Mines and Resources Canada, the Ontario Ministry of Energy, NRC, Ontario Hydro and the manufacturer (DAF Indal). The system functioned well and its output agreed reasonably well with the predictive model. The system was then ready for application in remote northern environments. The main problems found with the system had to do with output and applicability. There was an inherent limit to the fuel savings that could be achieved of about 25%. It was also recognized that retrofit situations could not be handled by mechanical coupling; electrical coupling would be required so that the wind turbine could be sited in the best wind location, possibly away from the existing diesel power plant.

In 1982, the Funding Committee comprised of NRC, Ontario Ministry of Energy, Ontario Hydro and DAF Indal put together the second phase of the development and testing at Sudbury. The project was to test stand-alone operation of the wind turbine, with the diesel generators shut down during good winds, in an attempt to increase fuel savings and establish the control criteria for electrical coupling. Fuel consumption for electrical and mechanical coupling were to be compared.

The results of the second phase project are contained within this report. More effort than was originally intended was put into establishing stand-alone operation (without the use of a storage medium). The effort resulted in establishing stand-alone operation on a manual basis, however it was discovered that an automatic stand-alone system without storage was not viable because of the variability of power input from the wind. Much was learned about the dynamics and stability of operation under such conditions especially as they apply to the VAWT.

The next step in the development of wind-diesel system technology therefore lies in the area of storage. Many countries in addition to Canada, including the U.S., Britain, Denmark and Sweden, also recognize the importance of storage. Various studies are looking at what level of storage is most appropriate. Storage of the order of seconds or minutes of rated wind power is relatively inexpensive, but requires a storage medium that can be charged and discharged at very high rates. There is also the question of how many diesel starts and stops are acceptable. Storage of the order of hours is expensive, but easier to design into a system and more reliable both technically and in terms of backup energy. Currently, battery storage is the most attractive energy storage, though new flywheel systems are also being considered.

Canada stands to gain by doing research, development and demonstration in this area since Canada is farther ahead than most countries in wind-diesel hardware development.

In addition to R.D.&D. work, there is also the need to demonstrate and acquire operating experience in actual installations. An electrically coupled wind-diesel system without storage will be installed in the remote community of Fort Severn, Ontario in the spring of 1986 and will provide useful data and operating experience. A smaller system with battery storage will be commissioned at the nearby community of Winisk, Ontario by the Ontario Ministry of Natural Resources.

The choice of wind-diesel system, whether it be with or without storage, will be determined by technical compatibility with existing supply systems, system size, reliability, and economics. An in-house study performed by the Ontario Ministry of Energy shows that existing wind-diesel equipment could be operated economically in a number of remote communities in Ontario. The potential for Canada as a whole would be much greater.

The potential world-wide market for wind-diesel systems is perceived to be large. It could develop into over a $10 million/year market once established.

Wind-diesel Steering Committee

Perspectives canadiennes de la technologie vent-diesel

Les récents travaux canadiens de développement de l'énergie éolienne ont commencé avec la réinvention de l'éolienne à axe vertical de Darrieus par le Conseil national de recherches du Canada (CNRC) au milieu des années 60. Le Programme de R&D sur l'énergie éolienne du CNRC a conduit à la mise au point, par des entreprises canadiennes, d'aérogénérateurs à axe vertical (EAV) d'une puissance initiale de 1 kW et actuellement d'une puissance de 50 kW à 4 MW.

À la fin des années 70, le gouvernement de l'Ontario et le CNRC ont mené conjointement l'essai d'un petit prototype de générateur hybride vent-diesel sur l'île de Toronto. Le projet a permis de démontrer la faisabilité du couplage vent-diesel et les résultats laissent penser que le couplage mécanique pourrait être plus simple et plus efficace que la mise en parallèle d'un aérogénérateur et d'un groupe diesel.

En 1980, un système vent-diesel à l'échelle commerciale de 100 kW avec couplage mécanique a été essayé à Sudbury (Ontario). Le système était composé d'une EAV de 35 kW couplée mécaniquement à l'un de deux groupes diesels de 50 kW reliés par un autosynchroniseur. Des batteries de résistances commandées par ordinateur simulaient une charge variable en fonction du temps typique d'une collectivité et une charge résistive "exutoire" absorbait l'excès de puissance généré en période de faible demande. Le projet était financé par Énergie, Mines et Ressources Canada, le ministère de l'Énergie de l'Ontario, le CNRC, Ontario Hydro et le fabricant (DAF Indal). Le système a bien fonctionné et la puissance fournie correspondait raisonnablement bien aux prévisions du modèle. Le système était alors près pour une application dans les régions éloignées du Nord canadien. Les

principaux problèmes avaient trait à la puissance fournie et à l'applicabilité. On a observé une limite inhérente d'environ 25 % aux économies possibles de combustible. Il fut aussi établi que le couplage mécanique n'était pas applicable lorsqu'il s'agissait de modifier des systèmes existants. Dans ce cas, le couplage électrique s'impose de façon que l'aéroturbine puisse être installée à l'endroit le plus favorable, éventuellement loin du groupe diesel existant.

En 1982, le comité de financement composé de représentants du CNRC, du ministère de l'Énergie de l'Ontario, d'Ontario Hydro et de DAF Indal, a défini la deuxième phase du développement et des essais à Sudbury. Le projet consistait à essayer l'aéroturbine en autonome, avec les groupes diesels arrêtés pendant les périodes de bon vent, dans le but d'essayer d'accroître les économies de combustible et d'établir les critères de régulation pour le couplage électrique. On devait aussi comparer la consommation de combustible avec un couplage électrique et un couplage mécanique.

Les résultats de la seconde phase du projet sont donnés dans le présent rapport. Les essais de fonctionnement en autonome (sans milieu de stockage) ont demandé un plus grand effort que prévu. On a réussi à faire fonctionner l'éolienne en autonome manuellement, mais on a découvert qu'un fonctionnement en autonome automatique sans stockage était impossible en raison de la variabilité de l'énergie éolienne. Les chercheurs ont beaucoup appris sur la dynamique et la stabilité des systèmes fonctionnant dans de telles conditions, surtout en ce qui concerne les EAV.

La prochaine étape de la mise au point de la technologie vent-diesel consiste donc à étudier le stockage. Outre le Canada, de nombreux pays, dont les États-Unis, la Grande-Bretagne, le Danemark et la Suède, reconnaissent aussi l'importance du stockage. Diverses études sont consacrées à la détermination du niveau de stockage le plus approprié. Un stockage de l'ordre de quelques secondes ou quelques minutes d'une puissance éolienne nominale est relativement peu coûteux, mais il est alors nécessaire d'avoir un milieu de stockage qui puisse être chargé et déchargé très rapidement. Il y a aussi le problème du nombre acceptable de démarrages et d'arrêts du générateur. Un stockage de l'ordre de plusieurs heures est coûteux, mais le système est plus facile à concevoir et il est plus sûr à la fois techniquement et en termes d'énergie d'appoint. À l'heure actuelle, les batteries constituent le système de stockage le plus attrayant, mais on envisage aussi de nouveaux systèmes basés sur les volants.

Le Canada tire profit des travaux de recherche, de développement et de démonstration dans ce domaine car il possède une grande avance sur la plupart des autres pays en ce qui concerne la mise au point du matériel vent-diesel.

En plus des travaux de R.D.&D., il est aussi nécessaire de faire des démonstrations et d'acquérir de l'expérience à l'aide d'installations réelles. Un système vent-diesel à couplage électrique, sans stockage, sera installé dans la collectivité éloignée de Fort Severn (Ontario) au printemps de 1986. Il fournira des données utiles ainsi que de l'expérience dans le fonctionnement d'un tel système. Un dispositif plus petit avec stockage par batteries sera mis en service dans la collectivité voisine de Winisk (Ontario) par le ministère des Ressources naturelles de l'Ontario.

Le choix d'un système vent-diesel, avec ou sans stockage, sera guidé par la compatibilité technique avec l'installation existante, la taille du système, la fiabilité et les aspects économiques. Une étude interne du ministère de l'Énergie de l'Ontario montre que l'équipement vent-diesel existant pourrait fonctionner économiquement dans plusieurs collectivités éloignées de l'Ontario. Le potentiel à l'échelle du Canada serait beaucoup plus grand.

Le marché mondial potentiel des systèmes vent-diesel apparaît vaste. Une fois établi, il pourrait dépasser les dix millions de dollars par an.

Comité directeur de la technologie vent-diesel

FORWARD

This report reviews the conclusions and recommendations of the Sudbury II Task 01 and 02 Reports, and presents the results of the Task 03 work.

The main results of the Sudbury II work are summarized as follows:

(1) Synchronizing of a wind driven alternator to a 60 Hz utility bus can be (and has been) routinely and automatically performed in a wide range of wind speeds.

(2) Utility requirements for frequency and voltage regulation were met by the system operating in the electrically coupled mode. Voltage excursions in the stand-alone operating mode were close to meeting the requirements.

(3) Stand-alone system performance can be improved through the use of an energy storage and recovery device. Stand-alone useful load carrying ability is presently limited by the power available from the lowest wind speed experienced during any period of interest. Recovery and return of excess wind gust energy (which at present is wasted) would increase the stand-alone load carrying ability. Reduced diesel operating hours, startups, fuel consumption, and maintenance would result.

AVANT-PROPOS

Le présent rapport résume les conclusions et les recommandations des rapports des tâches 01 et 02 du projet Sudbury II et donne les résultats de la tâche 03.

les principaux résultats du projet Sudbury II se résument ainsi :

1) La synchronisation d'un alternateur alimenté par énergie éolienne à un bus de 60 Hz d'un réseau de distribution peut être (et a été) réalisée de façon courante et automatique pour une large gamme de vitesses du vent.

2) Les exigences du système de distribution en ce qui concerne la régulation de fréquence et de la tension ont été satisfaites lorsque le système fonctionnait au mode couplage électrique. Lors d'essais de fonctionnement en automne, les exigences relatives à la tension ont été près d'être satisfaites.

3) Il est possible d'améliorer la performance du système autonome en utilisant un dispositif de stockage et de récupération de l'énergie. Avec les systèmes fonctionnant en autonome, la charge utile qu'il est possible d'alimenter est actuellement limitée par la puissance disponible quand les vents sont les plus faibles pendant la période considérée. La récupération et la fourniture de l'énergie en excès produite par les rafales de vent (qui est inutilisée à l'heure actuelle) augmenterait la charge que le système autonome pourrait alimenter. Il

en résulterait une diminution du temps de fonctionnement des générateurs diesel, du nombre de démarrages, de la consommation de combustible et de la maintenance.

1. BACKGROUND

1.1 Review of Sudbury I Project Results

The Summary Technical Report, Design, Development and Testing of a Vertical Axis Wind Turbine Assisted Diesel Generator System (March 30, 1984, L.A. Schienbein et al, DAF Indal Ltd.) provides a full description of Sudbury I system operation and performance.

The Sudbury I system consisted of a vertical axis wind turbine, mechanically coupled to a diesel via a shared synchronous alternator (Figure 1.1.1). The system configuration permitted the diesel to run when the wind turbine was shut down for lack of wind. The diesel was also compelled to run to provide frequency regulation when wind power alone could otherwise have carried the load. (The diesel engine governor regulated wind turbine and diesel speed and hence, electrical bus frequency.) Diesel output power was maintained at a minimum of 20% of diesel rated power to minimize "no-load" effects on diesel life. A supplementary "dump" load was provided to achieve an energy balance between available wind input power, mandatory minimum diesel input power, and the instantaneous power demand.

The report concluded that the test configuration could produce cost effective fuel savings and would be highly reliable in remote community applications. Some system limitations were identified:

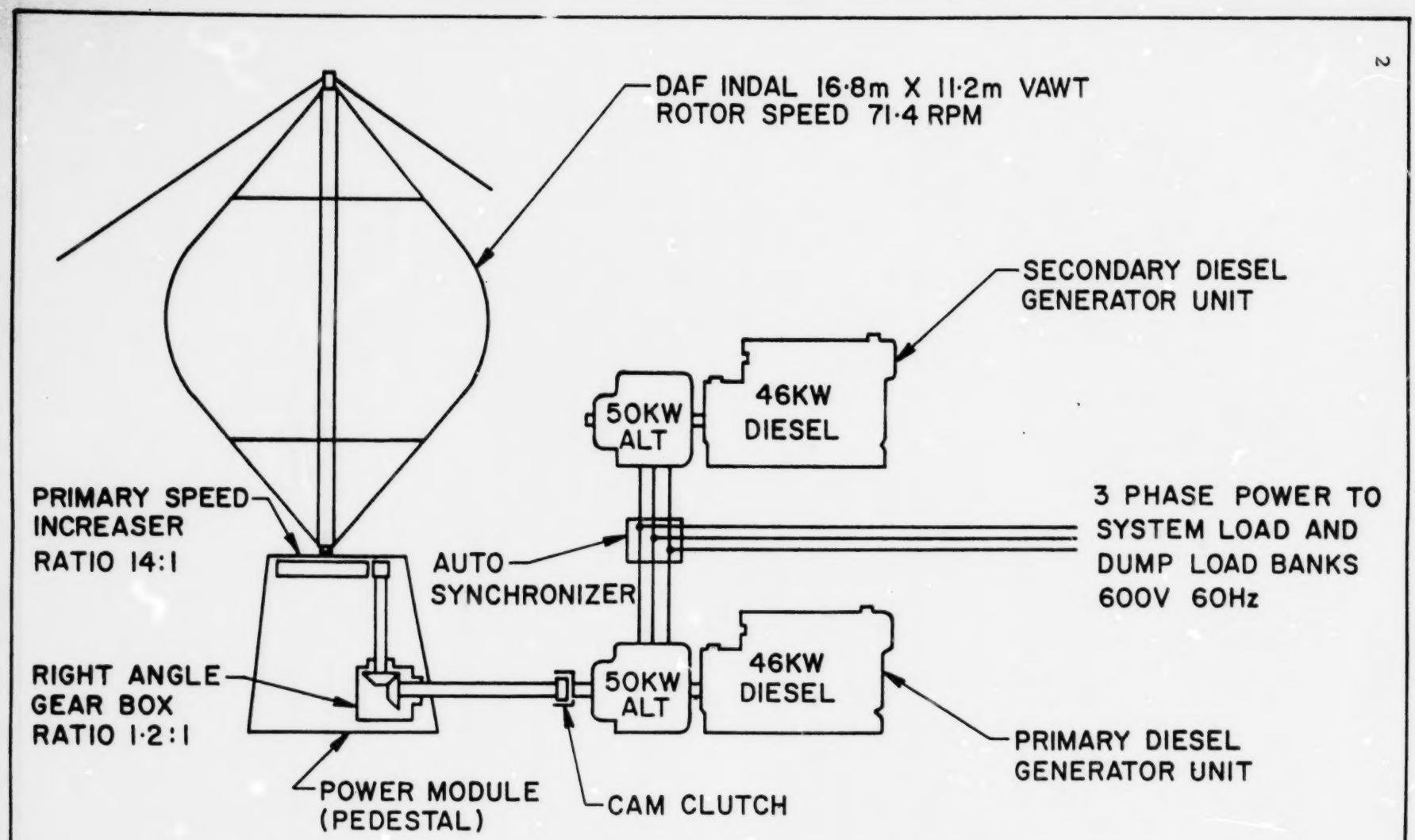


Figure 1.1.1 Schematic of the Prototype 100 kW Wind Turbine Assisted Diesel Generator System near Sudbury, Canada

(1) The mechanical link prevents geographic separation of the wind turbine from the diesel whenever separation would be desirable for the optimum siting of both.

(2) The 20% minimum load requirement imposed on the diesel and the requirement to run the diesel at all times means that significant amounts of energy are wasted when demand load is light, and/or winds are high.

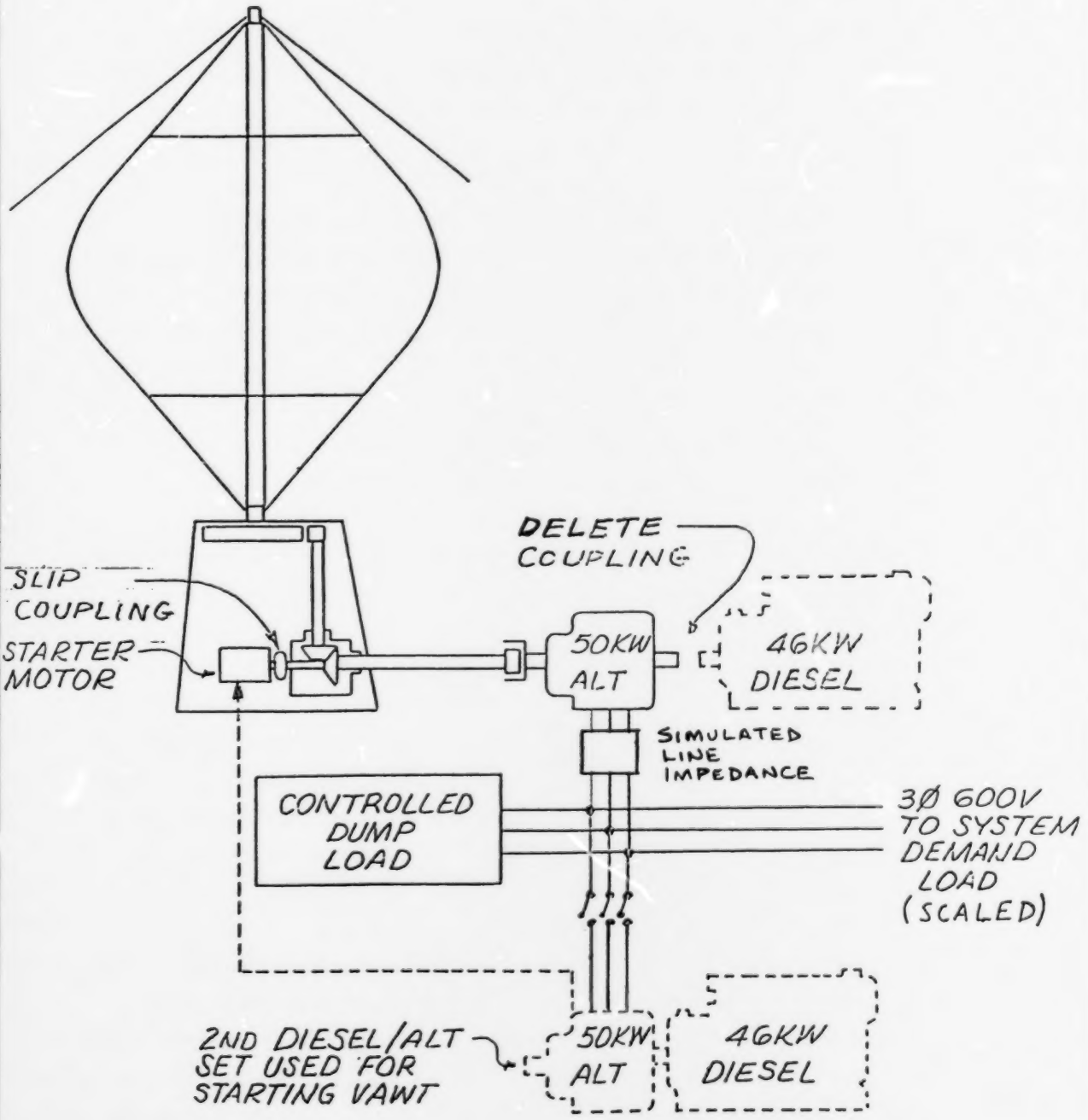
(3) The mechanical link was identified as the weakest point in an otherwise very reliable system.

The Sudbury II project grew out of the desire to overcome these limitations.

1.2 Review of the Sudbury II Proposal

The document Further Development and Testing of the Sudbury Wind Diesel Hybrid Power Plant (Sudbury II), DAF Indal, October 15, 1982, provides a detailed description of the proposed Sudbury II system, and the work to be performed.

The work was divided into three tasks. Task 01 was a proof of concept test utilizing existing test site components. The equipment was to be quickly reconfigured to permit wind turbine stand-alone operation and electrically coupled operation (Figure 1.2.1). In addition some mechanical modifications of the VAWT starting system were to be carried out, in order to reduce starter motor



TASK #1 CONFIGURATION
ELECTRICALLY COUPLED & STAND ALONE SYSTEM

Figure 1.2.1

inrush current. A device to simulate transmission line impedance was also to be installed between the wind turbine alternator (ALT #1) and the remaining diesel alternator (ALT #2).

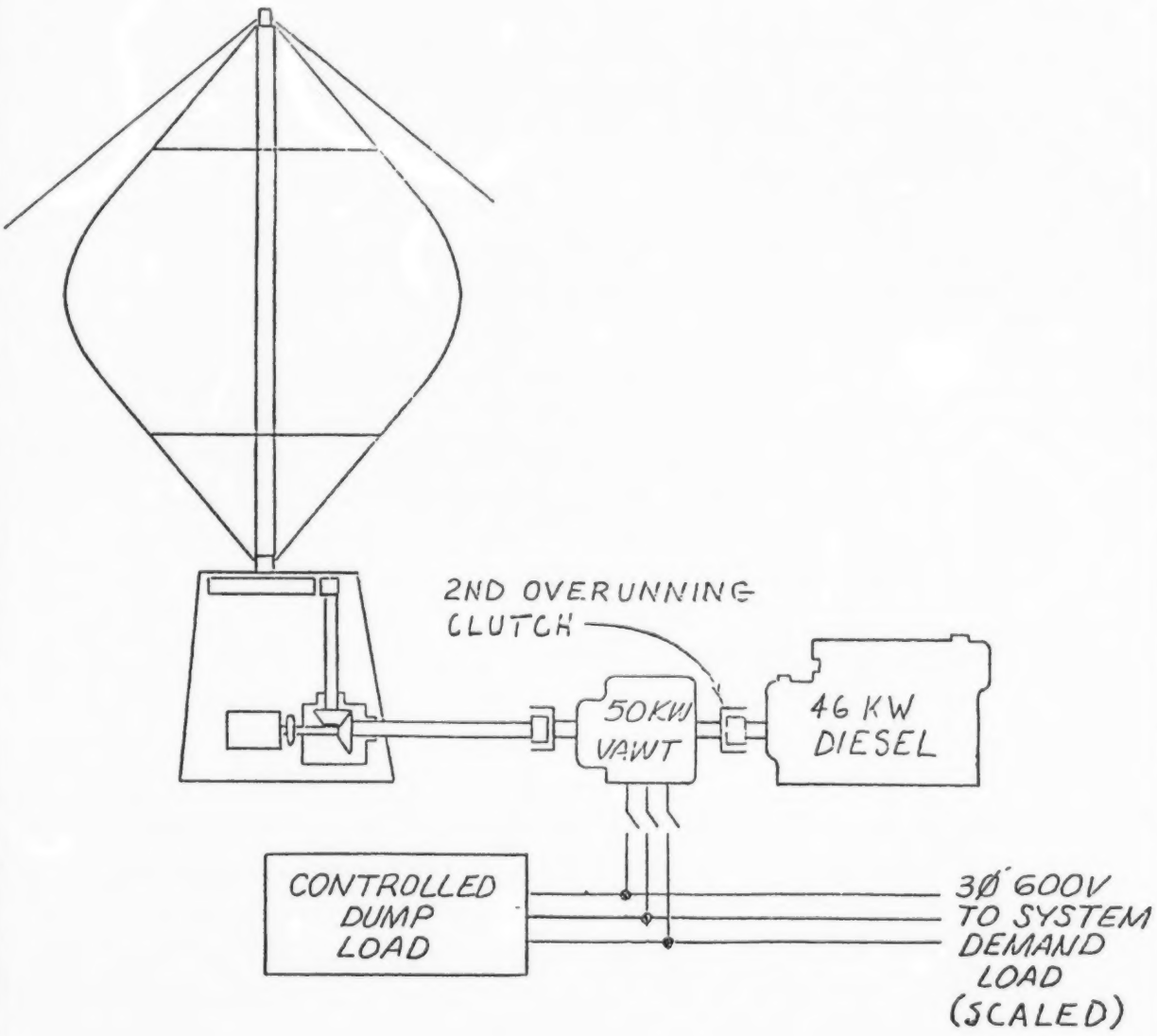
Task 01 allowed for project termination if early technical results were not favourable.

Contingent on favourable Task 01 results, Task 02 was to produce a fully recommissioned and automatic system. A combination of measurement, trial and error correction and simplified prediction was to be used to address system stability concerns. System performance measurements would be taken to establish fuel savings.

Task 03, as originally proposed, was to restore the Sudbury I mechanical configuration, with the addition of a second clutch between the #1 diesel and the #1 alternator (Figure 1.2.2). The Sudbury II controls strategy would be retained, to result in the ability to operate in three modes; mechanically coupled, VAWT stand-alone, or with either of the preceding modes electrically coupled to the #2 diesel alternator. Task 03, as outlined, was eventually deleted in favour of additional concentration on the Task 02 effort. The mechanically coupled variant was by this time thought to be of little market interest, due to the factors cited in Section 1.1.

1.3 Review of Sudbury II Task 01 Results, Conclusions and Recommendations

Refer to the Task 01 Report Stand-Alone and Electrically Coupled System Feasiblity for a detailed



TASK #3 CONFIGURATION
MECHANICALLY COUPLED/STAND ALONE SYSTEM

Figure 1.2.2

description of results, conclusions and recommendations. In summary, these were:

(1) Starter motor inrush current was reduced by a factor of at least two, through the installation of a centrifugal clutch on the starter motor shaft. (Sudbury I results had shown that start-up of the wind turbine required load shedding by the #2 diesel alternator set. The clutch eliminated this need.)

(2) Replacing the Sudbury I motor-driven variac dump load controller with a solid state controller improved the systems response when attempting to synchronize the VAWT to the diesel #2 bus, and during wind turbine stand-alone operation.

(3) Task 01 voltage and frequency excursions exceeded utility guidelines for the stand-alone mode, but met the guidelines during electrically coupled operation.

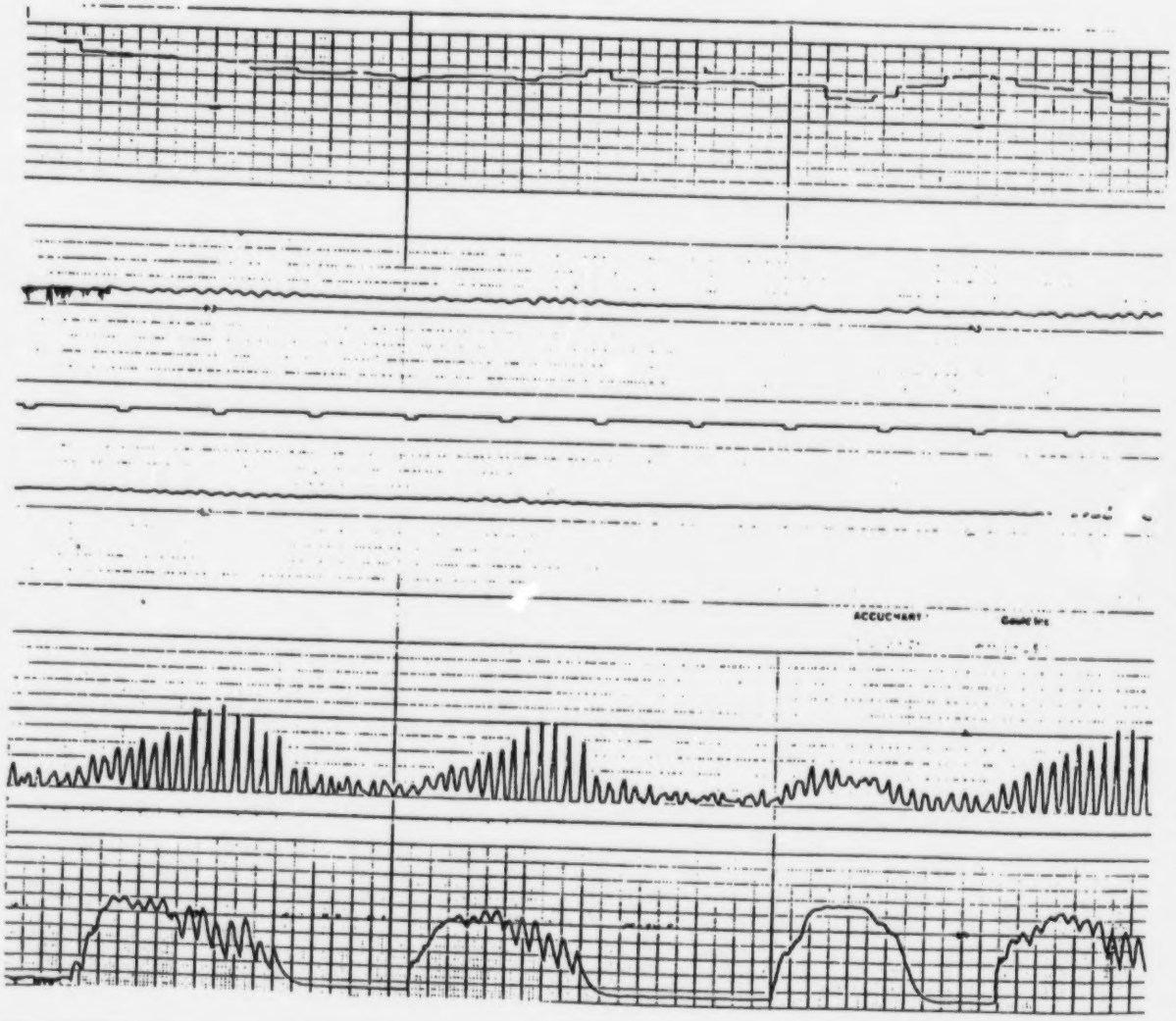
(4) Extreme torsional oscillations at approximately seven Hz were observed during stand-alone operation (Figure 1.3.1).

(5) There was an apparent need to upsize the power capacity of the dump load and its controller, as evidenced by problems in synchronizing the wind turbine to the diesel grid during high winds.

Figure 1.3.1

"STAND ALONE" OPERATION WITH NEW DUMP LOAD CONTROLLER

Chart Speed 25 mm/sec



1.4 Review of Sudbury II Task 02 Results, Conclusions and Recommendations

Refer to the Task 02 Technical Report for a detailed account of results. Summary, conclusions and recommendations from Task 02 follow.

1.4.1 Task 02 Electric Power Quality

After the size of the dump load and its controller were increased, satisfactory synchronization of the wind turbine to the diesel alternator and vice versa were repeatedly demonstrated without incident. Dump load feedback filtering and speed detector relocation re-resulted in frequency and voltage behaviour which were within the Ontario Hydro guidelines, with the marginal exception of "stand alone" voltage (See Figure 1.4.1.1).

These tests were carried out in wind speeds between 10 and 24 miles per hour.

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Figure 1.4.1.1

SUDBURY II TASK 02

Typical Operating Data

Operating Mode	Voltage Fluctuation		Frequency Fluctuation	
	Observed Worst Case Intermittent	Stated Objective Per Ontario Hydro IEEE Std. 519-1981	Observed Worst Case Intermittent	Stated Objective Per Ontario Hydro Guideline For Wind Diesel Systems
Electrically Coupled	± 0.7% @ 3.5 Hz	± 1 1/4% @ 3.5 Hz	± 0.7% @ 3.5 Hz	± 2.3% @ 3.5 Hz
Stand Alone	± 1.3% @ 7 Hz	± 0.83% @ 7 Hz	± 0.8% @ 7.0 Hz	± 1.0% @ 7 Hz

1.4.2 Task 02 Dynamic Analysis

It was first assumed that voltage transient behaviour would not be coupled in any important way with torsional dynamics. The waveform discontinuity due to dump load controller chopping occurs at 60 Hz on each phase, a frequency too high to excite any mechanical resonances. The system was therefore modelled as a series of rotating masses connected by torsional springs.

High speed shaft stiffnesses were measured. The first calculations and mechanical component data were then reviewed. New calculations predicted the existence of torsional natural frequencies at approximately eight and 10 Hz for the stand-alone system.

The preceding provided the data base for a subsequent forced response calculation by Mr. W. Moll of Ontario Hydro. The results of the latter calculation included prediction of a natural frequency for the electrically coupled system at 4.2 Hz. This was close to observed system activity at about 3.5 Hz. See Figure 1.4.2.1.

The W. Moll calculations also included the case of the stand-alone system with various fluid couplings inserted between the alternator and the VAWT rotor. As increasingly softer couplings were tried, the two system natural frequencies were observed to converge on the rotor-only natural frequency at about 8.3 Hz. Torque amplitudes were significantly decreased with the softest coupling. See Figure 1.4.2.2.

12 FIGURE 1.4.2.1 Electrically Coupled to Stand Alone Transition

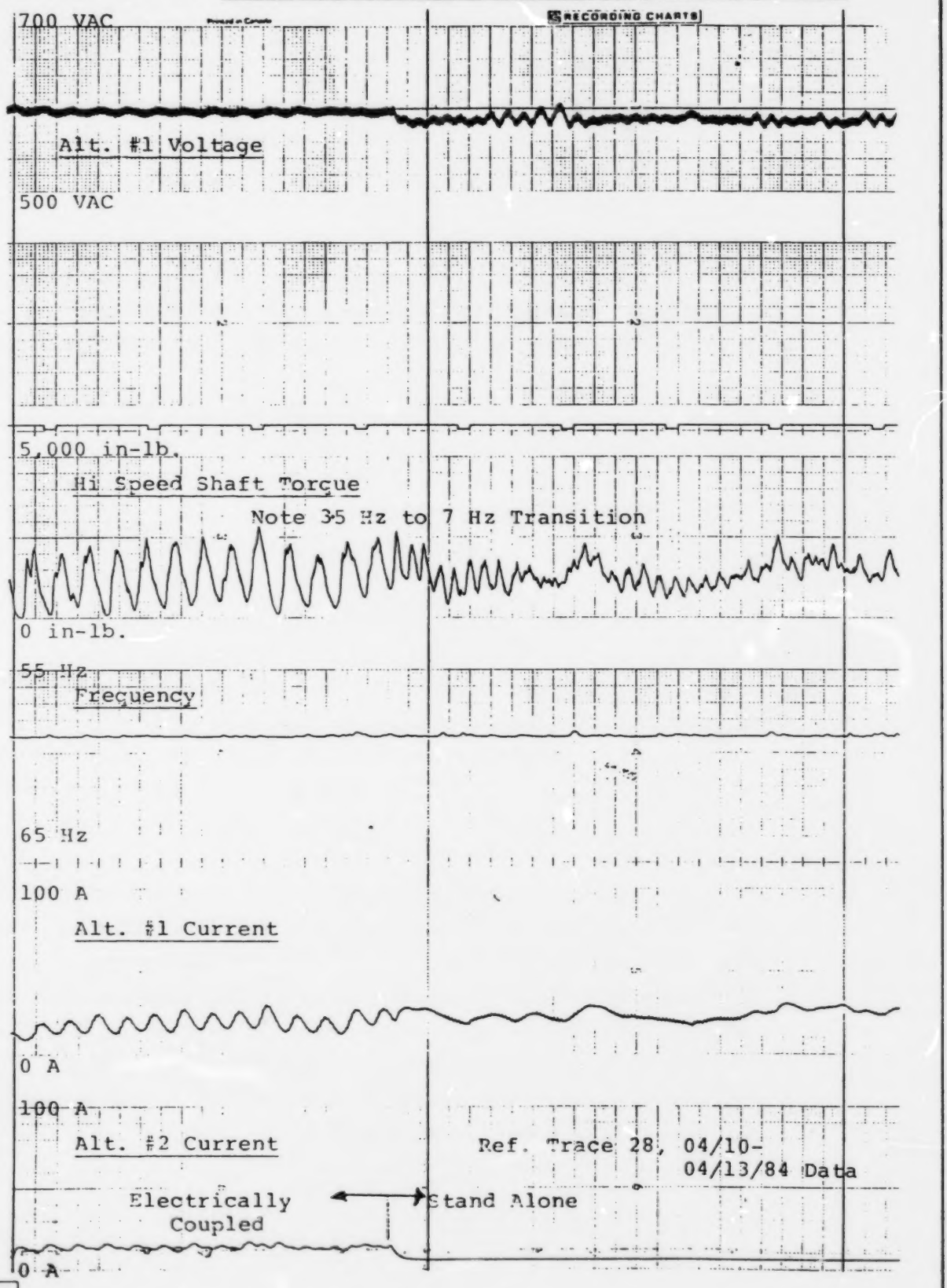
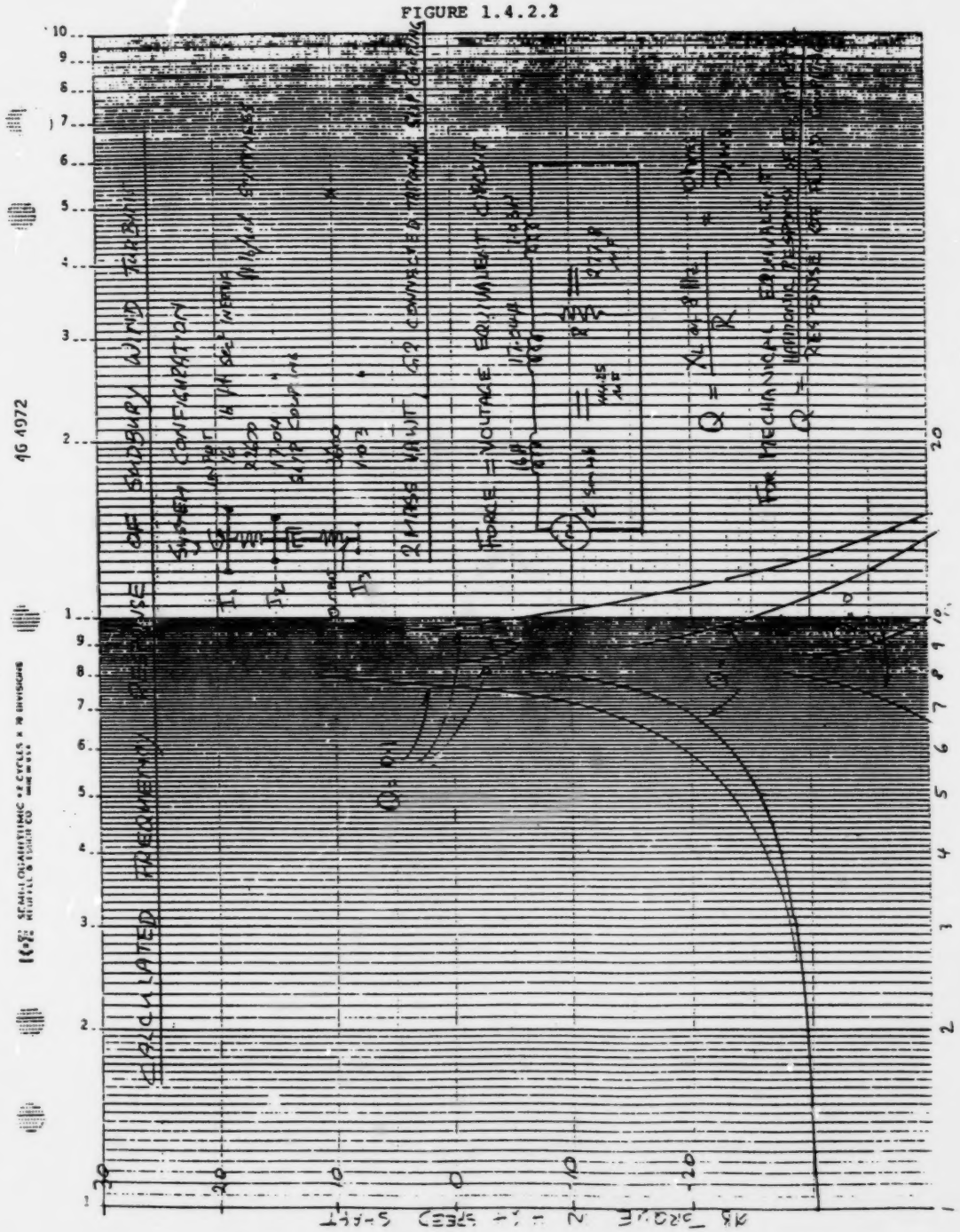


FIGURE 1.4.2.2



Sudbury I chart records were re-examined for behaviour corresponding to the Sudbury II stand alone seven Hz mode, and the 3.5 Hz electrically coupled mode.

Figure 1.4.2.3 shows the Sudbury I Diesel/Alt. #1 (only) system in operation. A comparison of this figure to the latter half of Figure 1.4.2.1 suggested the following:

(1) The "7 Hz" mode of the Sudbury II stand alone system is comparable to a "4.75 Hz" mode for the Sudbury I Diesel/ Alt. #1 (only) system. The increased inertia resulting from the presence of Diesel #1 in the Sudbury I system was thought to be the probable reason that the observed frequency for this mode was reduced to 4.75 Hz.

(2) The Sudbury I amplitude of torque oscillation appeared to be approximately half of the Sudbury II system amplitude. Windspeeds for Figures 1.4.2.1 and 1.4.2.3 were believed to be nearly the same. Ripple attenuation was thought to be partly due to damping from the Sudbury I Diesel #1. It was also concluded that it was partly due to greater separation of natural and forcing frequencies for the Sudbury I system.

Figure 1.4.2.4 showed the Sudbury I electrically paralleled configuration. This figure was compared to the Sudbury II electrically paralleled system represented by the first half of Figure 1.4.2.1. Figure 1.4.2.1 showed the characteristic Sudbury II 3.5 Hz torque ripple, and a virtual absence of the two per rev torque ripple observed in Figure 1.4.2.4 for Sudbury I.

FIGURE 1.4.2.3
Sudbury I VAWT & Diesel #1 (only) Torsional Dynamics
(Record 1201 of 08/25/82)

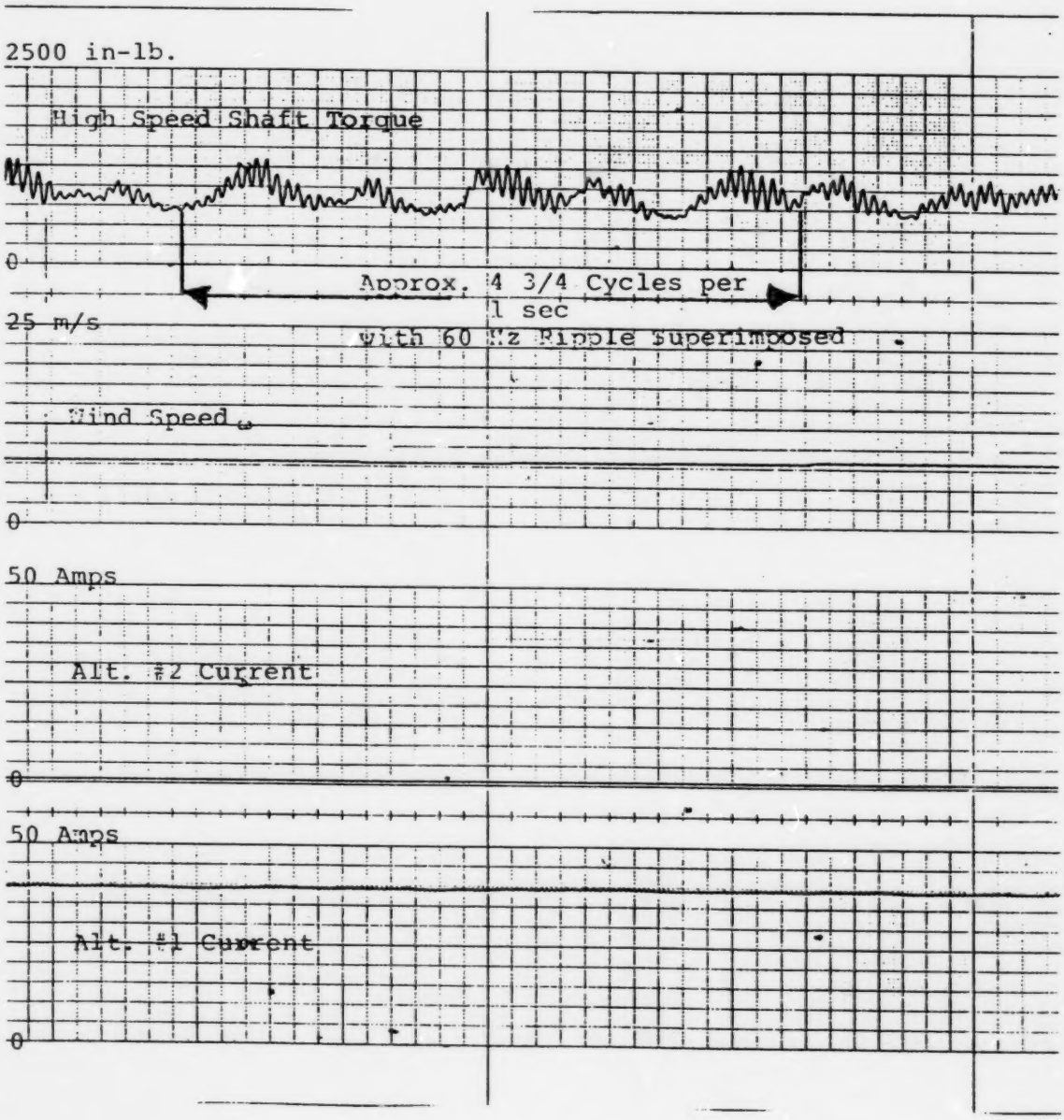
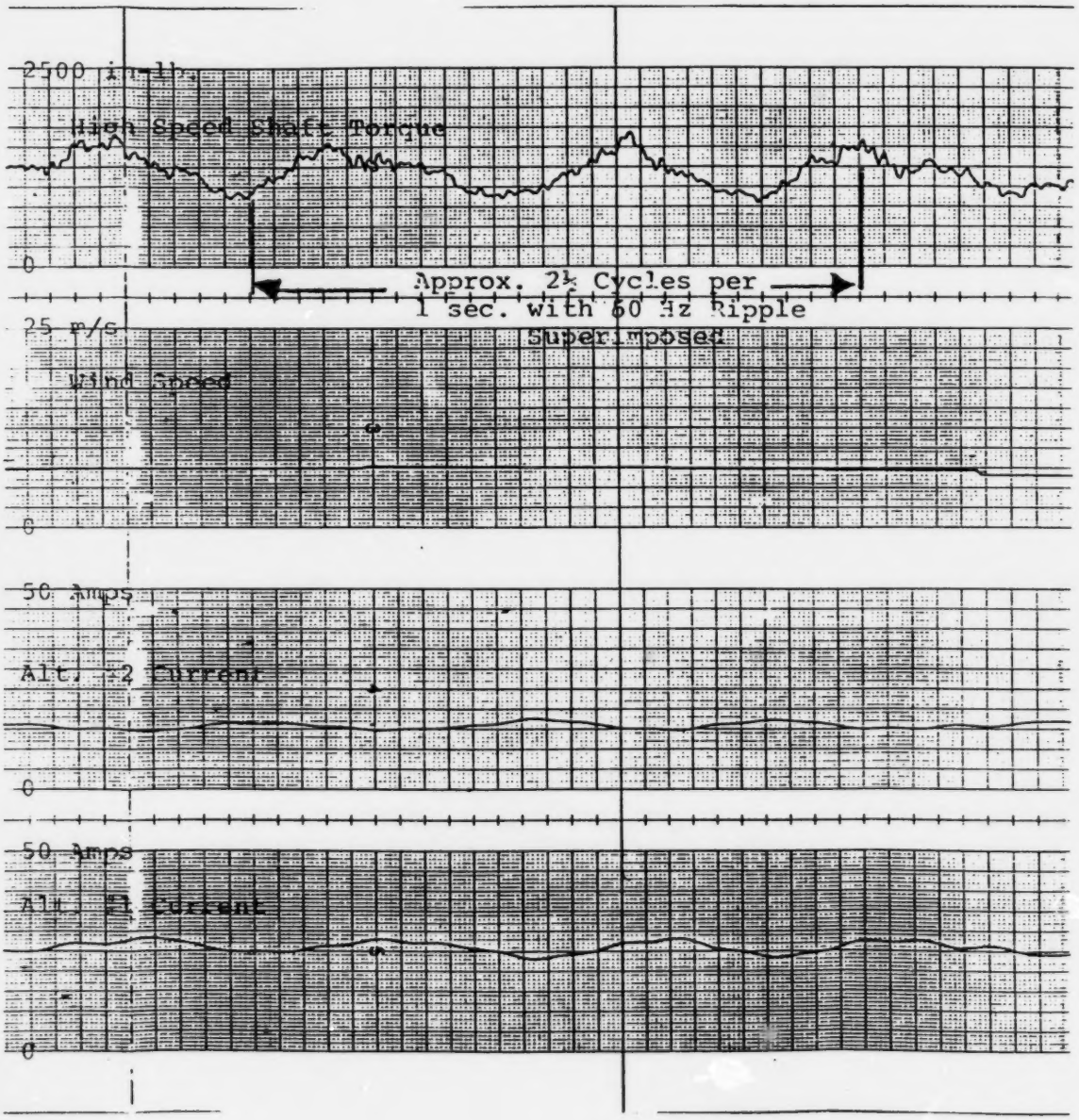


FIGURE 1.4.2.4

Sudbury I VAWT/Diesel #1 and Diesel #2 Torsional Dynamics
(Record 1201 of 08/05/82)



Conversely, strong harmonics greater than two per revolution were not obvious in the Sudbury I figure.

To compare expected behaviour of Sudbury II with Sudbury I, DAF Indal developed a computer program "TORDY2" to predict undamped natural frequencies. Figure 1.4.2.5, the resulting fan plot, includes predictions and observations of first order natural frequencies for all configurations.

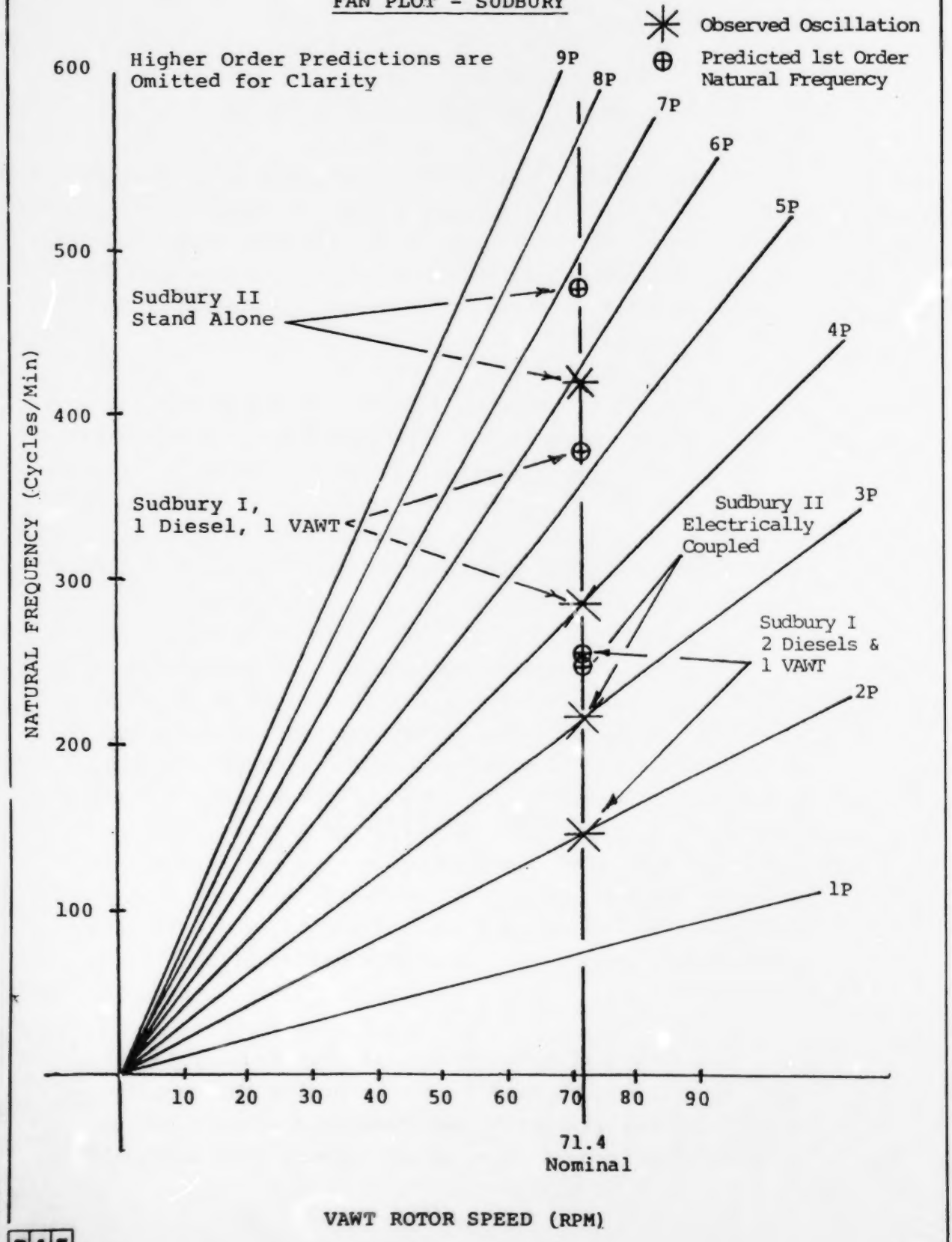
The fan plot shows that the observed dominant torsional response frequencies coincide closely in all cases with some VAWT rotor forcing frequency. The model, for example, predicted natural frequencies of 4.1 and 4.2 Hz for the Sudbury I and II electrically coupled systems, respectively, but there appears to be little response at these frequencies.

One possible explanation for this difference in behaviour was that estimates for electrical coupling stiffness, specifically alternator impedance, were not very accurate. The predicted natural frequencies may therefore be nearer to the forcing frequencies. If the electrical coupling was "softer" than assumed, the forcing frequencies might coincide with the revised natural frequency predictions. Verification of this hypothesis (to be carried out in Task 03) would require experimental measurement of electrical coupling stiffness.

An additional possibility was that Sudbury II dump load activity might have been reinforcing the usually weak three per revolution aerodynamic forcing function. Task 03 chart record examples of Sudbury II electrically

FIGURE 1.4.2.5

FAN PLOT - SUDBURY



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coupled operation with the dump load switching on and off were not available to verify this. Comparative data were expected to result from Task 03 work, which would include application of a dump load feedback notch filter tuned to 3.5 Hz. It was noted that Sudbury I dump load controller response rates precluded the possibility of reinforcement of any three per rev aerodynamic forcing function.

One way to possibly reduce system response to the forcing functions would be to greatly increase the system first order natural frequencies. It was concluded that only a small increase in system natural frequency could be achieved by changing the high speed shaft soft "rubber" coupling to a stiffer gear coupling. In the case of the electrically coupled system, this was as likely to result in worse dynamic behaviour as it was in an improvement, because of the uncertain location of the real natural frequency relative to the three per revolution forcing function.

A similar conclusion applied to softening the high speed drive train. Furthermore both the stand-alone and electrically coupled system natural frequencies would likely move toward the stronger two per rev forcing function.

The only mechanical improvement which could be made with confidence would have been the installation of a fluid coupling, as suggested by Ontario Hydro. (Viscous damping would dissipate system torsional vibration energy.)

The VAWT electrical and mechanical overspeed signals and dump load speed error signals are taken from what would be the wind turbine side of the proposed fluid coupling. The coupling would permit speed excursions and increased wind turbine absolute speed relative to the alternator shaft speed. The impact of a fluid coupling on system control would have to be determined.

The cost of procuring and installing a fluid coupling would be substantial, exclusive of the cost impact on the controls. Therefore, it was recommended that system performance testing proceed with the present mechanical arrangement, and that if a fluid coupling was pursued, it be separately funded.

The pronounced three per rev response of the electrically coupled system underscored earlier concerns that some unintentional aerodynamic asymetry of the rotor existed. It was recommended that this possibility be investigated under separate funding.

1.4.3 Revised Task 03 Objectives Resulting from Task II

The following group of recommendations were submitted under separate cover and were accepted by Ontario Hydro, the project managers, for implementation in Task 03, with the exception of Item 1.4.3.7. These items replaced the original Task 03 Work Plan set out in DAF Indal's proposal. The originally proposed Task 03 equipment configuration was judged to have limited immediate applications.

Recommendations 1.4.3.1, 1.4.3.2, 1.4.3.3, 1.4.3.5, and 1.4.3.7 were related to persistent torsional dynamic stability problems encountered with the system. Although power quality was generally within utility guidelines, marginal torsional stability was a remaining source of concern.

Item 1.4.3.4, 1.4.3.8, 1.4.3.9 and 1.4.3.10 dealt with rescheduling to Task 03 the system fuel consumption tests and project close-out activity.

1.4.3.1 7 Hz Notch Filter

"Check the frequency response of the existing 7 Hz notch filter, which due to circuit adjustments may now be out of calibration. Make modifications or adjustments to circuit values as appropriate to ensure that (2) the notch centre frequency coincides accurately with the observed system natural frequency and (b) the notch frequency rejection is as high as possible."

1.4.3.2 3 1/2 Hz Notch Filter

"Design and build a second notch filter at approximately 3.5 Hz which is switched into the dump load control circuit only when the two alternators are synchronized. This may be instead

of, or in addition to, the seven Hz notch filter as determined by field tests. It may also require the use of a different low pass filter in the electrically coupled mode. The circuit will be optimized as in 1.4.3.1 above for notch centre frequency and rejection ratio."

1.4.3.3 A.V.R. Power Supply

"Rewire the Alternator 1 Automatic Voltage Regulator (A.V.R.) power supply from the more stable Alternator 2 output to reduce the voltage excursions of Alternator 1. This avoids subjecting No. 1 A.V.R. to the electrical spikes generated by the dump load controller on the Alternator 1 output voltage, and thereby avoids the resultant voltage surges caused by random A.V.R. behaviour."

1.4.3.4 Review/Readjust System Set Points

"As presently set up, the VAWT does not off load the diesel significantly during electrically coupled operation. The system set point frequencies and droop curves will be reviewed carefully and any re-adjustments found necessary or desirable will be made before starting any final system fuel saving tests. This could involve the switching in of an offset signal to the dump load control set points once the two alternators are synchronized."

1.4.3.5 System Performance Tests

"Performance testing will be carried out during, and subsequent to Tasks 1.4.3.1 through 1.4.3.4 to verify improvements in system behaviour and to generate a new set of chart records."

1.4.3.6 Review Results

"At this point the test results will be reviewed either in Toronto or on site in Sudbury by Ontario Hydro. The main objective of this review will be to decide whether system behaviour is deemed acceptable or further action in the form of a fluid coupling in the high speed shaft is necessary. In the former case Item 1.4.3.7 below will be omitted."

1.4.3.7 Fluid Coupling

"Select, procure and install a suitable fluid coupling in the high speed shaft as a replacement for the present flexible rubber coupling. The objective of this is to increase the viscous damping and thereby reduce the amamplification factor of the torsional natural frequencies.

Note that this change will almost certainly result in changes to the system natural frequencies and hence require supplementary changes to the filter circuits discussed in 1.4.3.1 and 1.4.3.2.

Finally, a repeat of the Performance Testing of 1.4.3.5 will be required to document and quantify system behaviour."

1.4.3.8 Fuel Consumption Testing

"A test procedure will be prepared to cover a necessarily shortened version of the long term fuel consumption tests. Once satisfactory system behaviour has been achieved a formal test period will be initiated with testing carried out in accordance with the agreed procedure."

1.4.3.9 Prepare Report

"Following the Performance and Fuel Consumption Testing, a report will be prepared summarizing the Phase II work carried out and the results of the test work."

1.4.3.10 De-Commissioning

"This task includes removing rental test equipment and some permanent test equipment and tools from the site that are not required during periods of inactivity, as well as securing the site for an indefinite period of inactivity."

2. SUDBURY II TASK 03 RESULTS

2.1 System Stability

2.1.1 Electrical Coupling Stiffness Measurement and Revised Natural Frequency Predictions

An improved value of electrical coupling stiffness for the three phase inductor-in case was obtained by measurement, using the procedure described in Appendix A. A second stiffness value was then inferred for the three phase inductor-removed case, using a calculation procedure similar to the method used for original estimates by Ontario Hydro in Task 02. These two values represented the electric coupling stiffnesses for the Sudbury II case and the Sudbury I case, respectively.

Improved natural frequency predictions for both cases were then produced using the program "TORDY2". This program is described in the Task 02 report. The results are shown on the fan plot of Figure 2.1.1.1.

2.1.2 Installation of a 3.5 Hz Notch filter

In accordance with Section 1.4.3.2, a 3.5 Hz notch filter was installed on the dump load control circuit to attenuate dump load activity at that frequency during electrically coupled operation. The results, shown on the chart record of Figure 2.1.2.1, indicate that when the filter is active, most of the 3.5 Hz (three per rev) activity is supplanted by activity at 2.4 Hz (two per rev).

FIGURE 2.1.1.1

Fan Plot - Electrically Coupled Systems

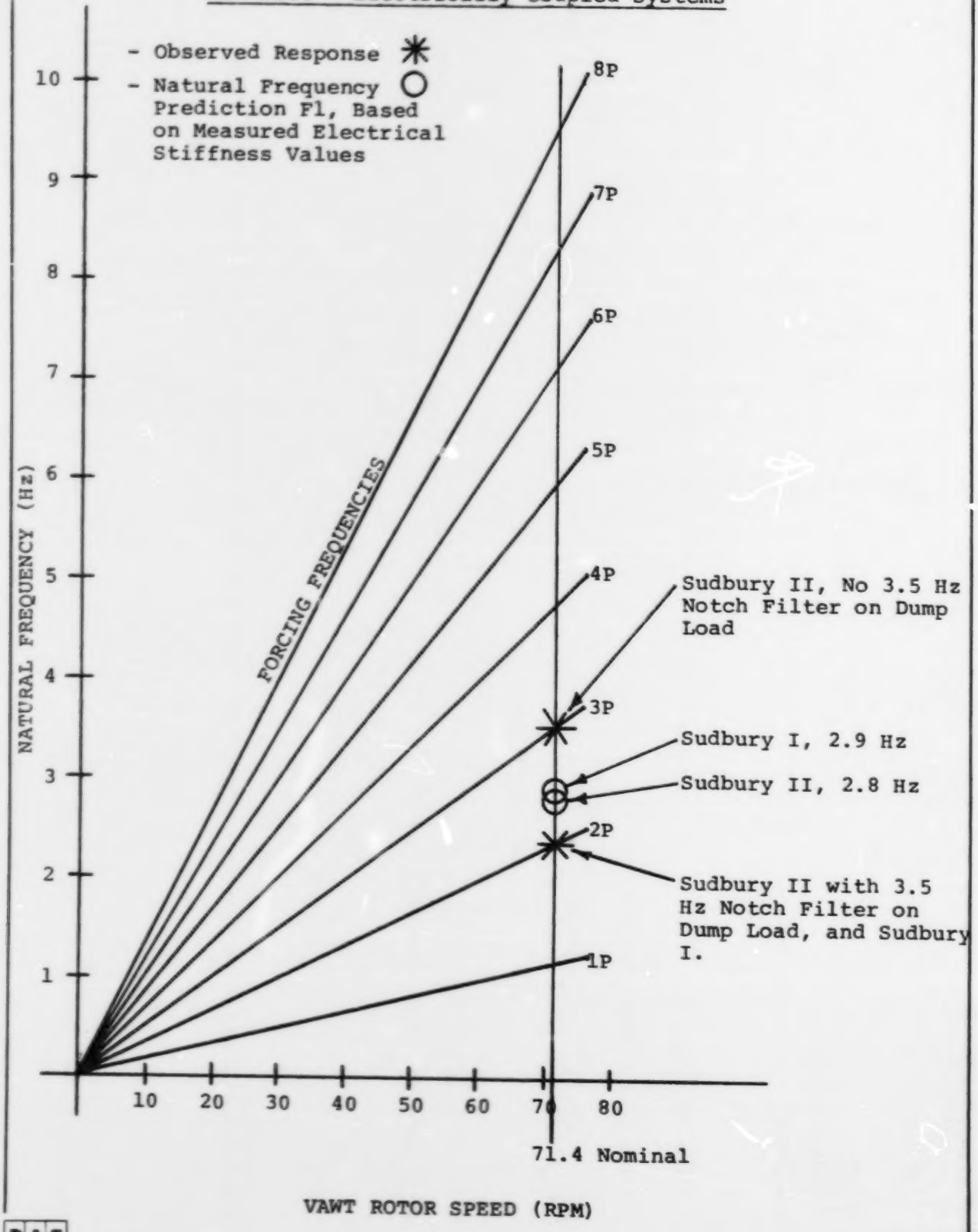

Figure 2.1.2.1 Effects of 3.5 Hz Dump Load Control Filter on Electrically Coupled Operation (from Run #8 of Aug. 15/84)

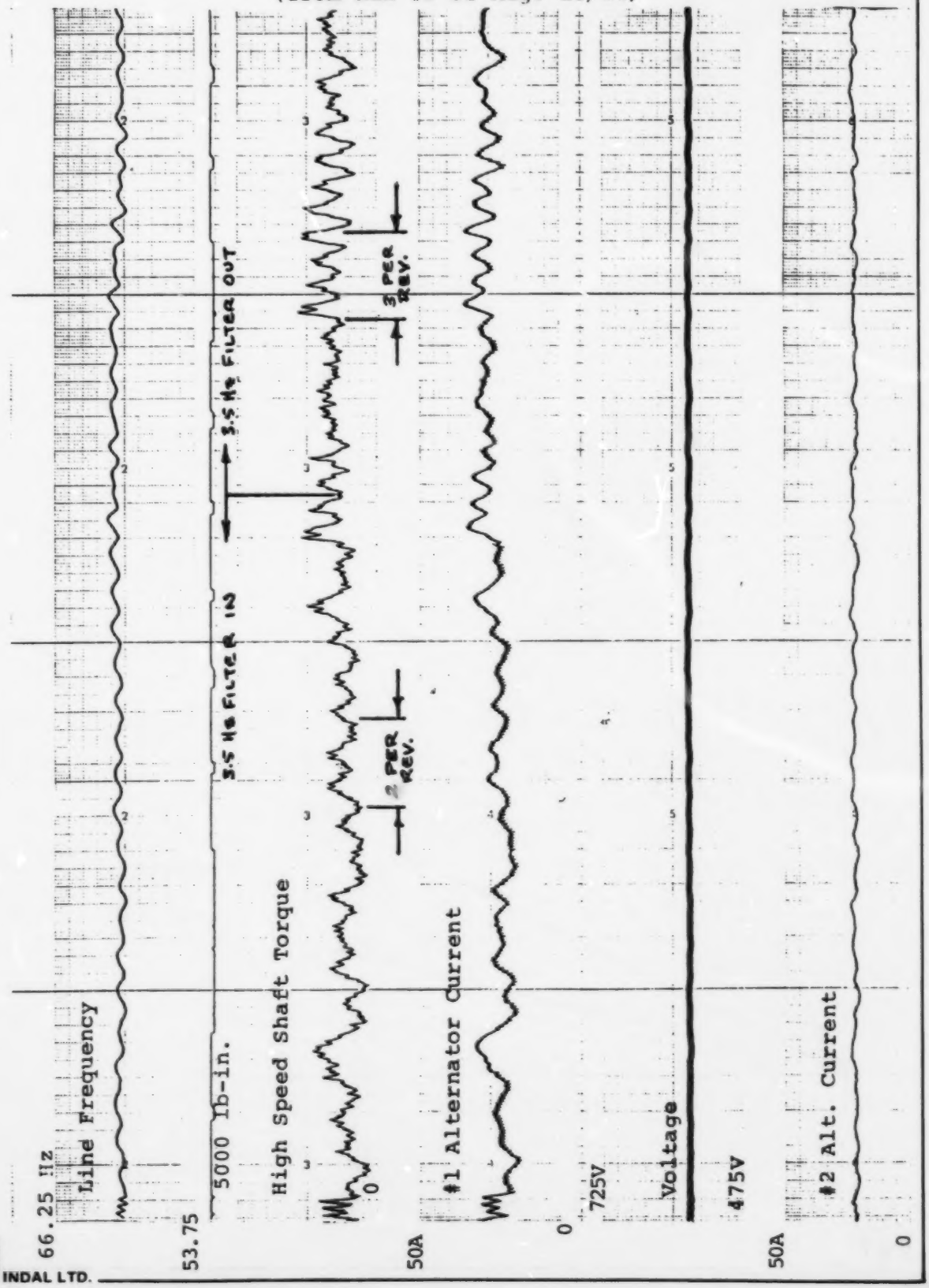

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Figure 2.1.2.2 shows a composite of dump load controller feedback filter characteristics for the seven Hz notch/ notch/one Hz roll-off filters, with and without the 3.5 Hz notch filter superimposed. At 3.5 Hz, the dump load response amplitude would be almost five times as great without the 3.5 Hz filter, as it would be with the 3.5 Hz filter.

The remaining two per rev oscillation is the familiar aerodynamic signature of a two bladed vertical axis wind turbine and is normally the strongest forcing function. The forcing function amplitudes seen in the trace are within expectations, and do not suggest a significant level of reinforcement by the dump load.

2.1.3 Re-centering of the Seven Hz Notch Filter

An existing notch filter which had a centre frequency of 7.9 Hz was replaced by a filter having a centre frequency of 7.0 Hz in accordance with ideas expressed in Section 1.4.3.1 of this report.

Steady state results for the stand-alone system are shown in Figure 2.1.3.1. It was observed that seven Hz peak to peak amplitudes with the filter in were reduced by about 50% compared with the "no seven Hz notch filter" case. To put this result in perspective, Figure 2.1.3.2 shows a torque trace from Sudbury I single mechanically coupled diesel operation. On it can be seen two per rev and four per rev torque ripple with 60 Hz ripple superimposed (60 Hz coincides with a 1200 RPM four cycle 6 cylinder diesel detonation frequency). The Sudbury I 60

FIGURE 2.1.2.2 Composite of a Dump Load Feedback Filter Characteristics
(1 Hz Roll-off low pass, 3.5 and 7 Hz Notch)

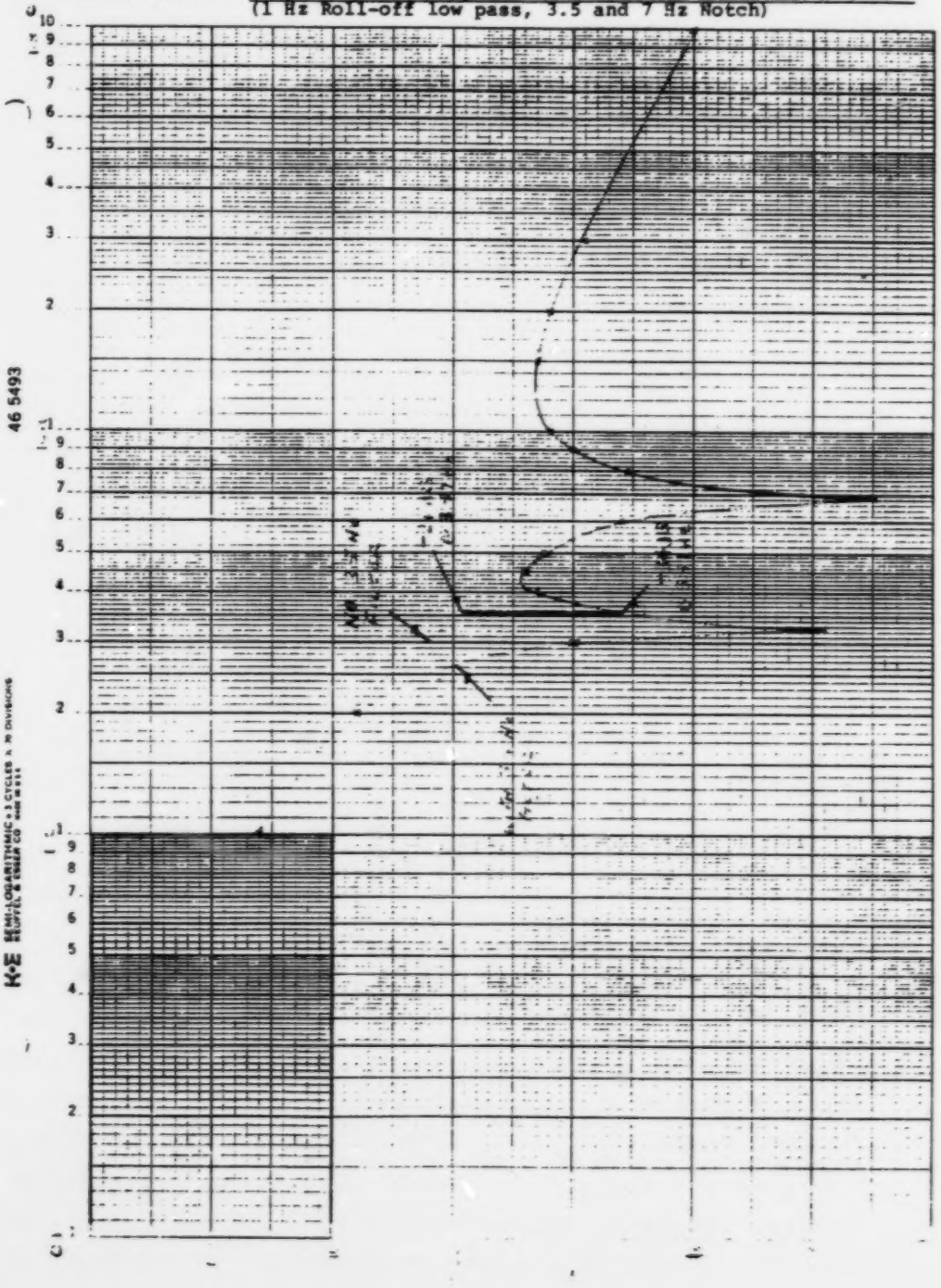


Figure 2.1.3.1 Effect of a 7 Hz Notch Filter on Steady State Stand-Alone Torque Ripple

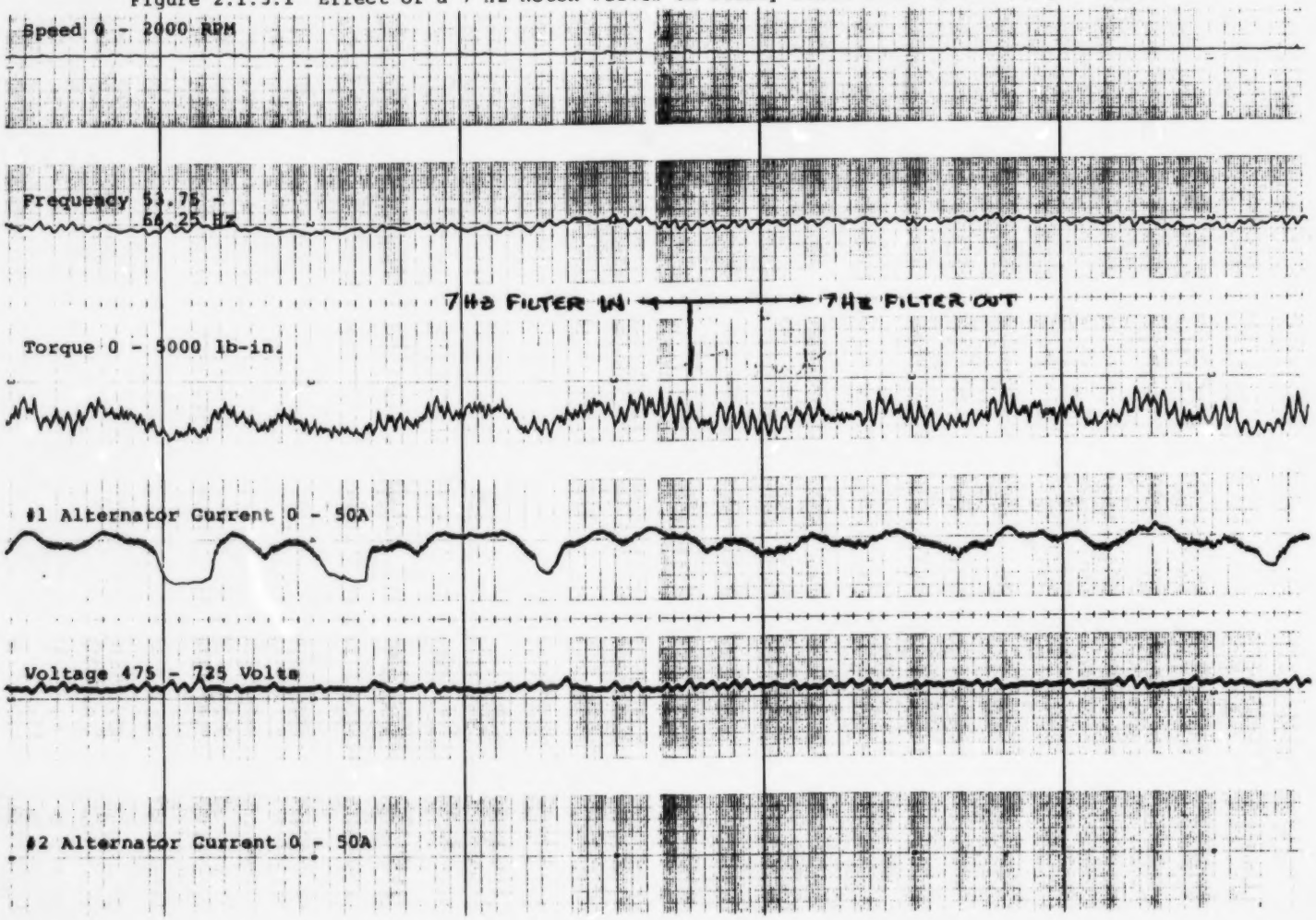
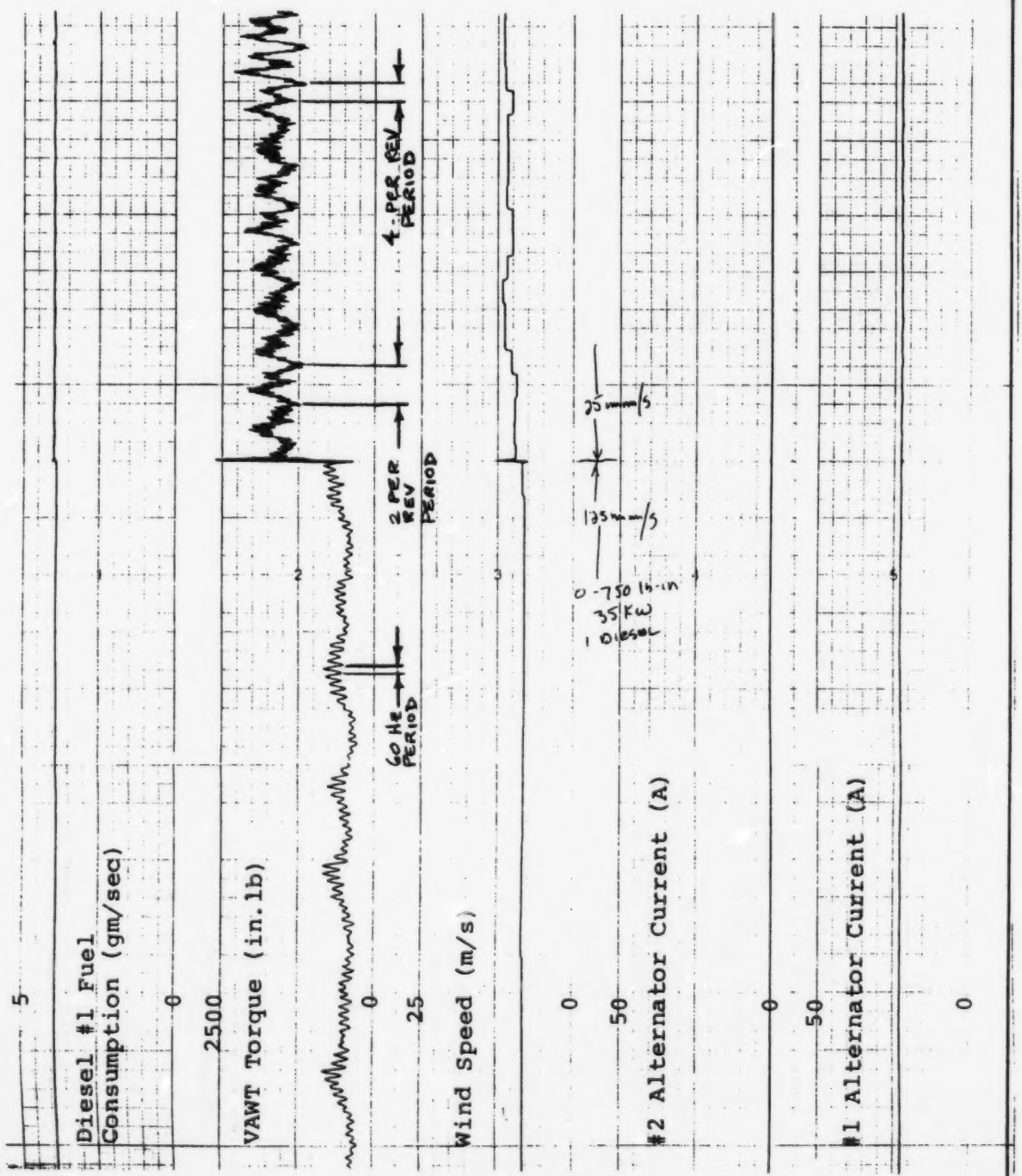

Speed 0 - 2000 RPM
Frequency 53.75 - 66.25 Hz
7Hz FILTER IN
7Hz FILTER OUT
Torque 0 - 5000 lb-in.
#1 Alternator Current 0 - 50A
Voltage 475 - 725 Volts
#2 Alternator Current 0 - 50A

Figure 2.1.3.2 Sudbury I Single Diesel Operation



Hz peak to peak amplitude is roughly the same as the Sudbury II seven Hz peak to peak amplitude with filter in. While this is not conclusive proof that either system is or was acceptable, it suggests that the level of seven Hz torsional disturbance on the standalone Sudbury II system approaches mechanical design expectations for diesel driven alternators.

2.2 Task 03 System Response to "Long Term" Changes in Load and Wind Speed

Appendix B is a summary of observations made by Ontario Hydro representatives who witnessed system automatic operation. The document is self explanatory and adaptations of conclusions presented in it have been included in the present report.

2.3 Task 03 System Fuel Savings

The following work was carried out in accordance with objectives stated in Sections 1.4.3.5 and 1.4.3.8.

2.3.1 Test Procedure: Diesel without VAWT

To provide a baseline (no wind turbine) fuel consumption curve, test runs of 20 minutes duration with constant demand load were carried out. Nominal demand loads were 5, 10, 15 ... 40 kW. Total plant load corresponding to each demand load was measured.

2.3.2 Results: Diesel without VAWT

Fuel consumption versus total plant load is plotted in Figure 2.3.2.1, along with similar data taken during the Sudbury I program. As expected, fuel consumption performance of the engine has not changed.

2.3.3 Test Procedure: Diesel Electrically Coupled to VAWT

The system was run in the electrically coupled mode against selected demand loads. The histogram counts and fuel consumption were logged for one minute periods. Average windspeed was calculated from the histogram counts and fuel consumption was plotted as a function of wind speed. The one hundred and fourteen test runs covered wind speeds from five to 13 m/s.

2.3.4 Results: Diesel Electrically Coupled to VAWT

Test results are given in Figures 2.3.4.1 and 2.3.4.2.

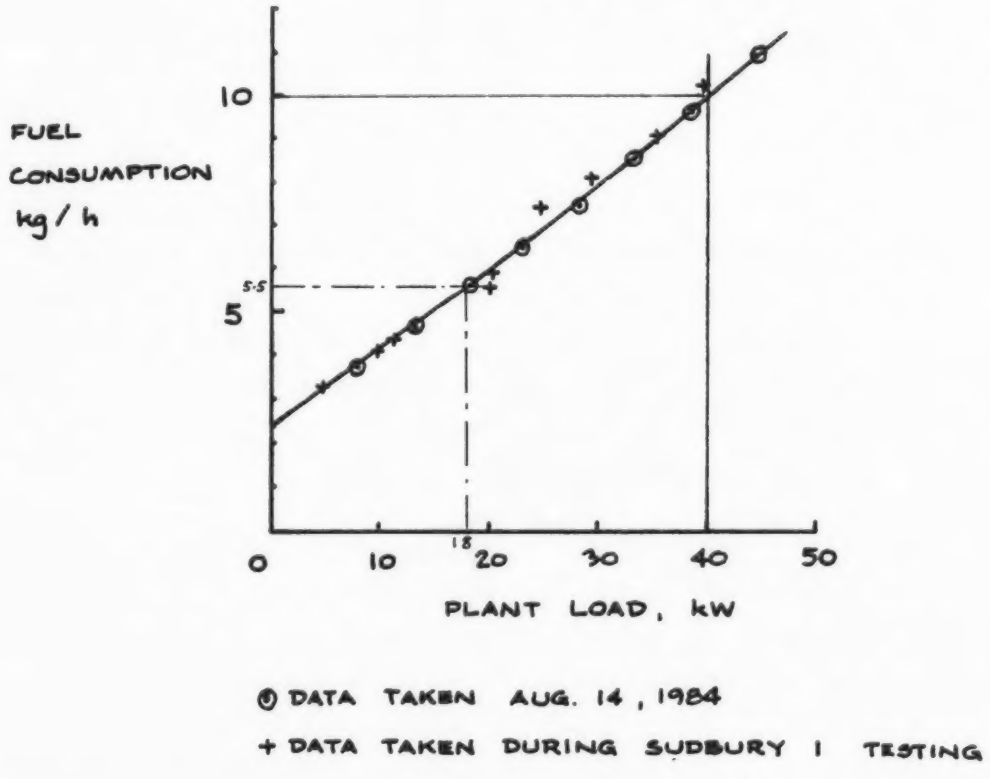


Figure 2.3.2.1 Fuel Consumption Rate vs. Plant Load - No VAWT

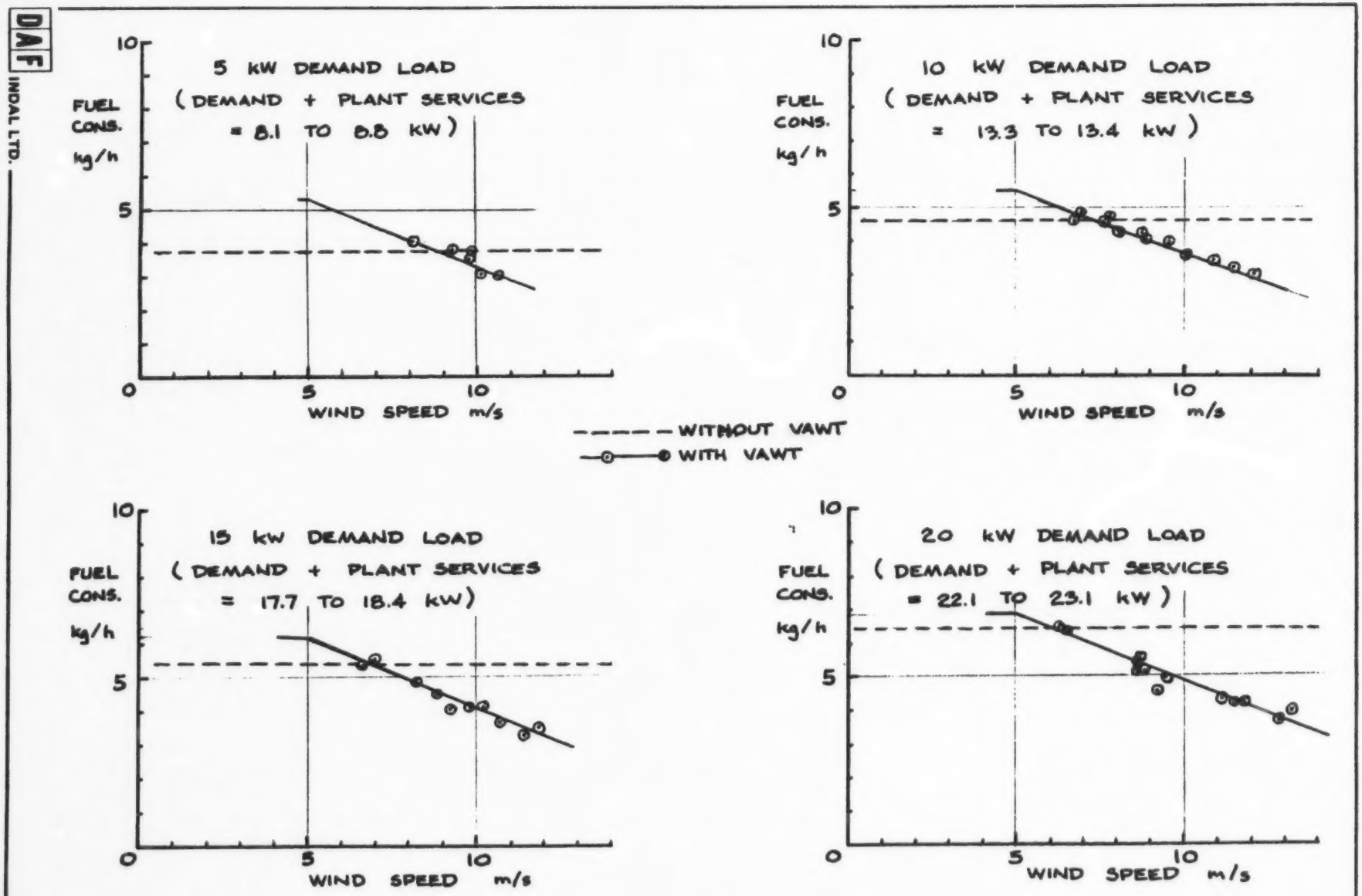


Figure 2.3.4.1 Fuel Consumption Rate vs. Wind Speed - Electrically Coupled System - Demand Loads 5 to 20 Kw

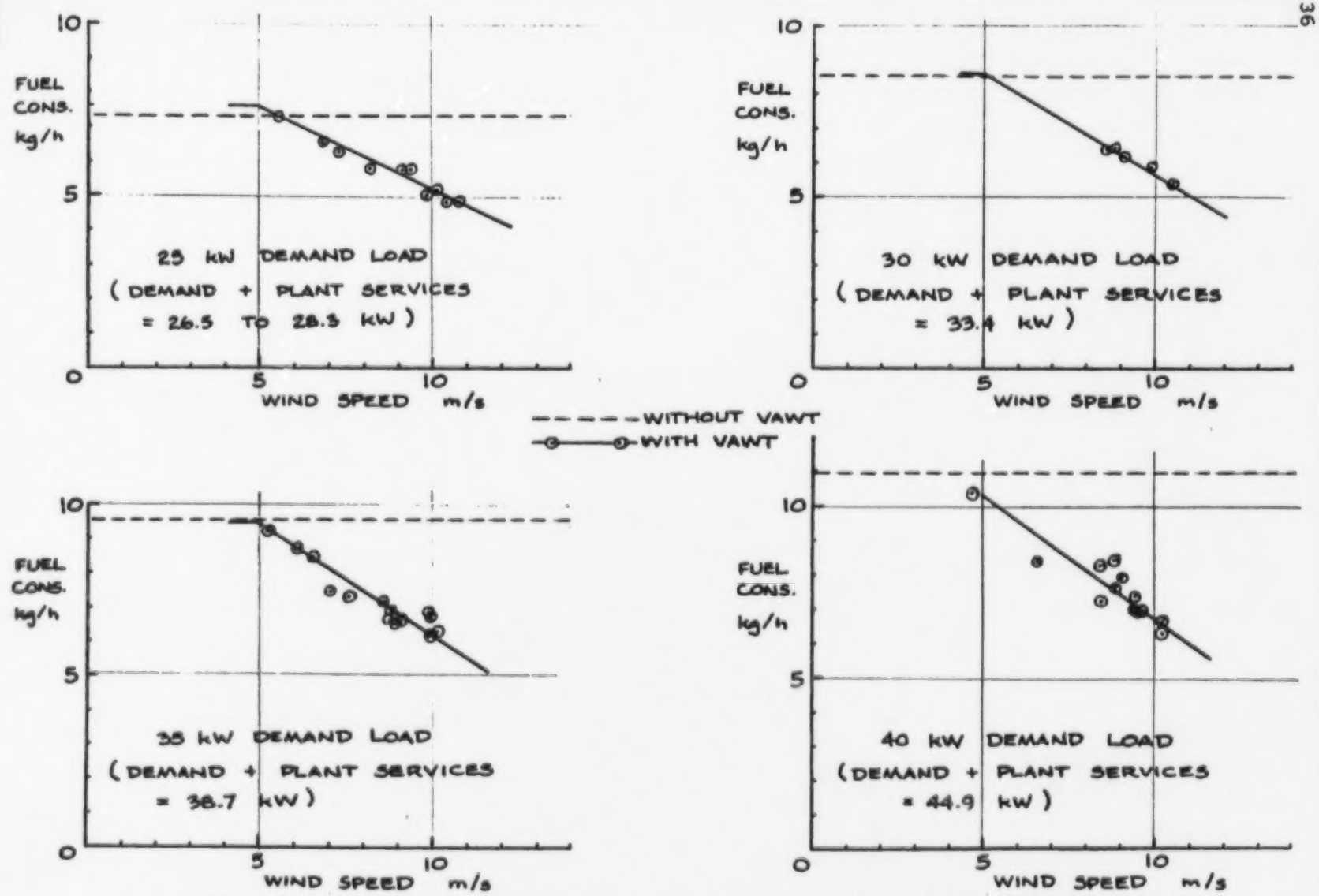

10
FUEL CONS. kg/h
5
0
5
10
WIND SPEED m/s
25 kW DEMAND LOAD
(DEMAND + PLANT SERVICES = 26.5 TO 28.3 kW)
30 kW DEMAND LOAD
(DEMAND + PLANT SERVICES = 33.4 kW)
WITHOUT VAWT
WITH VAWT
35 kW DEMAND LOAD
(DEMAND + PLANT SERVICES = 38.7 kW)
40 kW DEMAND LOAD
(DEMAND + PLANT SERVICES = 44.9 kW)

Figure 2.3.4.2 Fuel Consumption Rate vs. Wind Speed - Electrically Coupled System - Demand Loads 25-40 kW

Comparisons of the fuel consumption performance of the electrically coupled Sudbury II plant and the mechanically coupled Sudbury I plant can be made by studying Figure 2.3.4.3. Note, however, that the total plant load at Sudbury includes variable plant services such as heating and lighting. At demand loads of 30 kW or greater (total plant load 33 kW or greater) the fuel consumption of the electrically coupled system was close to that of the mechanically coupled system. At lower demand loads, where there was dump load activity, the electrically coupled system used more fuel than the mechanically coupled system.

Empirical equations relating fuel consumption to plant load and wind speed were derived from the experimental data. For the electrically coupled system the equations are

1. $F = F_O \frac{kg}{h}$, if $V \leq 5$ m/s

2. $F = F_5 - \frac{dF}{dV} \times (V-5) \frac{kg}{h}$, if $5 < V \leq 13$ m/s

3. $F = F_5 - \frac{dF}{dV} \times 8 \frac{kg}{h}$, if $V > 13$ m/s

4. $F_O = 2.3 + (\text{plant load}) \times .178 \frac{kg}{h}$, if plant load ≤ 18 kW

5. $F_O = 5.5 + (\text{plant load} - 18) \times .195 \frac{kg}{h}$, if plant load > 18 kW

6. $F_5 = 5.3 \frac{kg}{h}$, if plant ≤ 12 kW

7. $F_5 = 5.3 + (\text{plant load} - 12) \times .15 \frac{kg}{h}$, if plant load > 12 kW

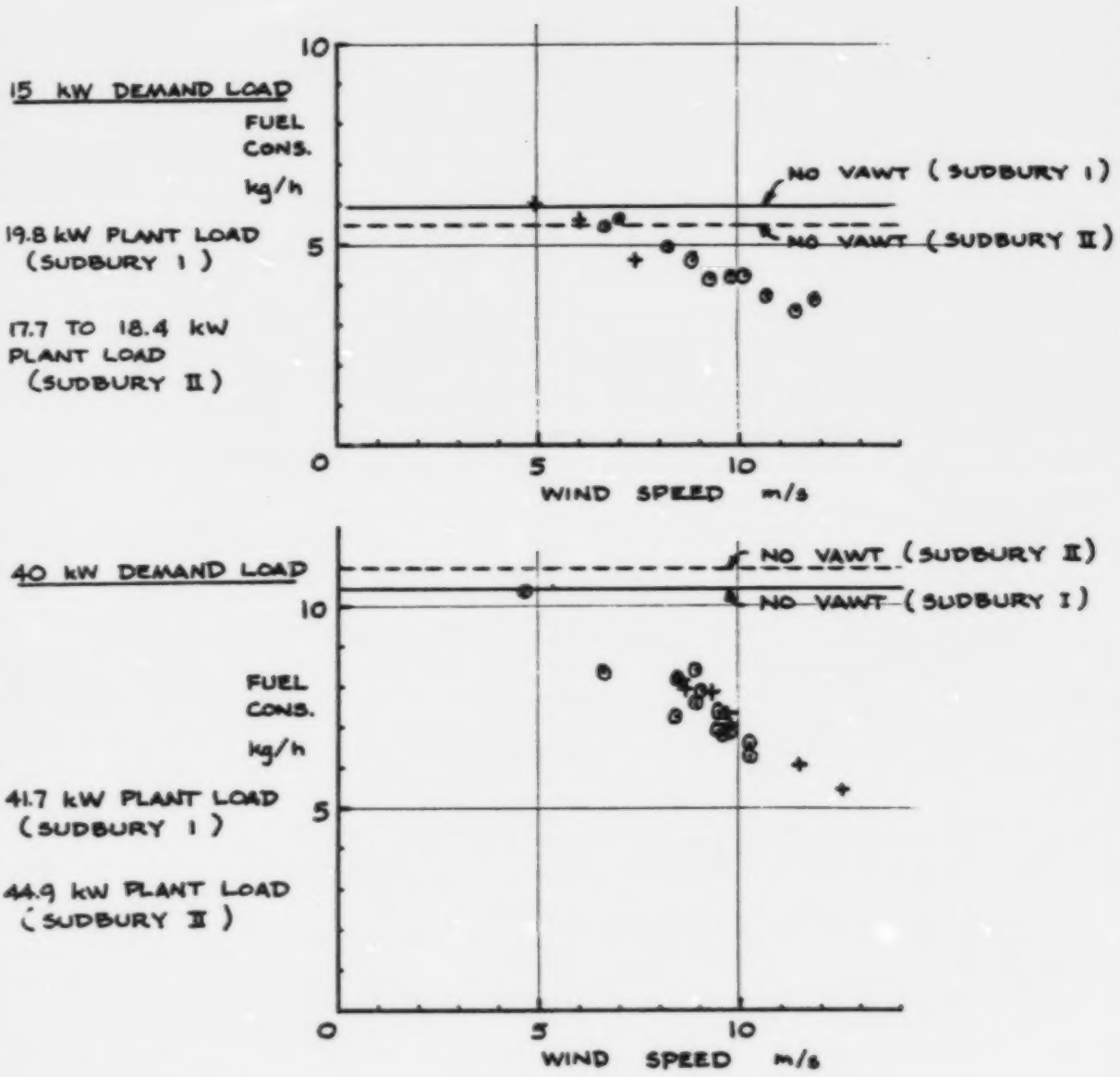


Figure 2.3.4.3 Comparison of Fuel Consumption Rates of Electrically Coupled and Mechanically Coupled Systems

8. $DF/dv = .39 \frac{kg}{h\ m/s}$, if plant load $\leq$ 22 kW

9. $Df/dv = .39 + (\text{plant load} - 22) \times .0156 \frac{kg}{h\ m/s}$
if plant load > 22 kW

F = fuel consumption rate for given plant load and wind speed.

F_o = fuel consumption rate for given plant load and no VAWT.

F_5 = fuel consumption rate for given plant load and wind speed = 5 m/s.

V = wind speed.

$\frac{dF}{dV}$ = slope of fuel consumption rate vs. wind speed plot.

Calculations of annual fuel consumption were based on preceding empirical equations. The assumed demand load histogram had a peak of 36.25 kW. Frequencies of demand load occurrence are given in the following table.

Demand Load Histogram

Demand Load, kW	Frequency of Occurrence	Demand Load, kW	Frequency of Occurrence
12.50	.001	25.00	.040
11.75	.138	26.25	.058
15.00	.065	27.50	.033
16.25	.084	28.75	.039
17.50	.143	30.00	.044
18.75	.064	31.25	.016
20.00	.094	32.50	.017
21.25	.048	33.75	.004
22.50	.039	35.00	.001
23.75	.062	36.25	.001

With a constant plant services load of 3 kW, the annual useful energy output (demand plus plant services) would be 206010 kWh. The calculation method reflected increased fuel consumption due to dump load activity, but the dumped energy was not included in the calculation of useful energy output.

A Rayleigh wind speed distribution was assumed. Figure 2.3.4.4 shows annual fuel consumption versus annual average wind speed. Fuel savings for the electrically coupled VAWT relative to the no VAWT case were predicted to be 5.7% when the average wind speed is 5.5 m/s (12.3 mph) and 19.2% when the average wind speed is 10 m/s (22.4 mph).

For comparison, similar calculations were done for a system in which the VAWT is mechanically coupled to a diesel generator set through an overrunning clutch. The following empirical fuel consumption equations were derived from Sudbury I data.

1. $F = F_o \frac{kg}{h}$, if $V < 5 \frac{m}{s}$ or $V > 18$ m/s

2. $F = F_5 - \frac{dF}{dV} \times (V-5) \frac{kg}{h}$, if $V \geq 5 \frac{m}{s}$

3. F is never less than $(F_o - 5.1) \frac{kg}{h}$

4. F is never less than $4.2 \frac{kg}{h}$

5. $F_o = 2.3 + (\text{Plant Load}) \times .178 \frac{kg}{h}$, if Plant Load ≤ 18 kW

6. $F_o = 5.5 + (\text{Plant Load}-18) \times .195 \frac{kg}{h}$, if Plant Load > 18 kW

7. $F_5 = F_o \frac{kg}{h}$

8. $\frac{dF}{dV} = .67 \frac{kg}{h\ m/s}$

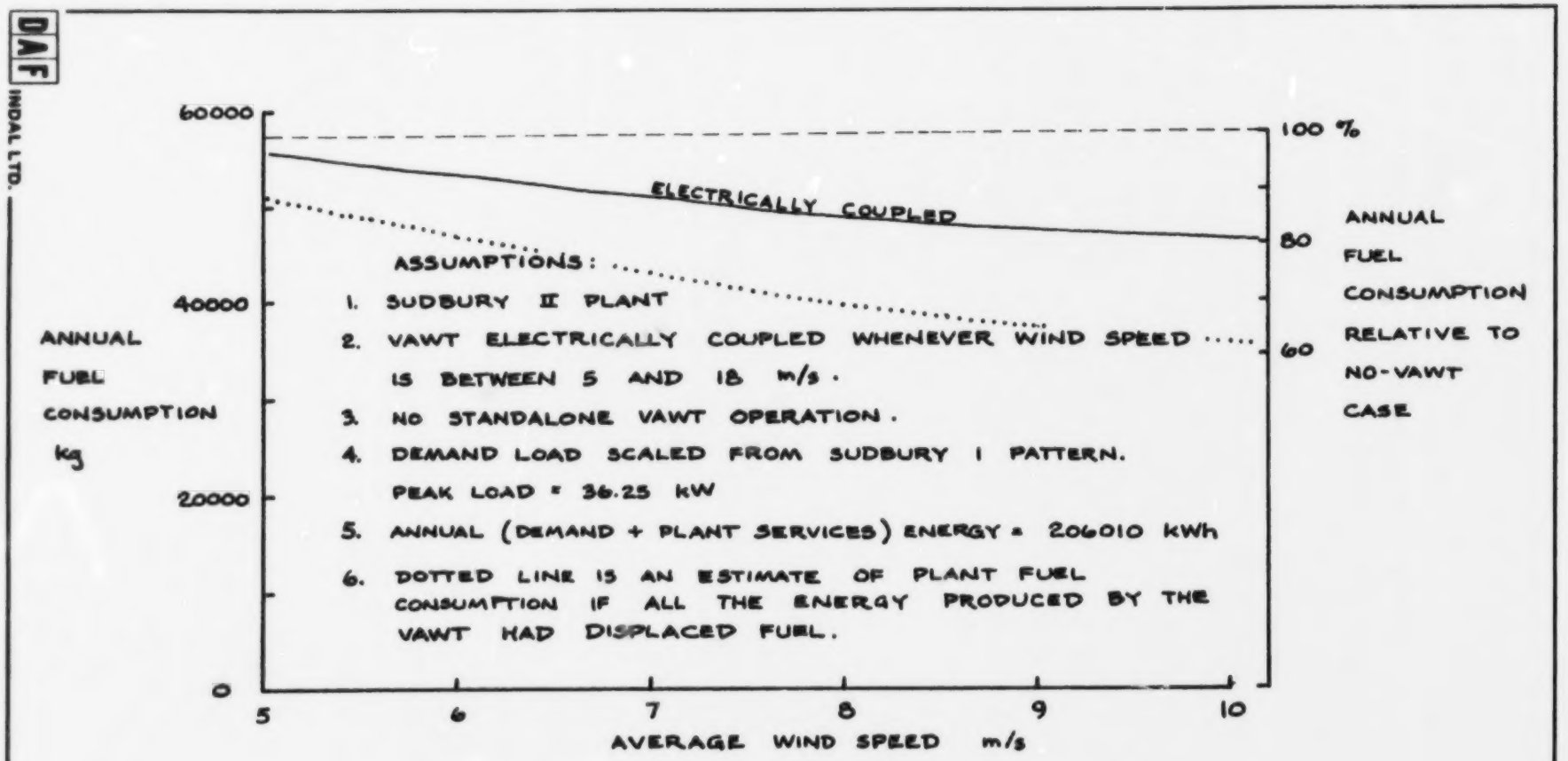


Figure 2.3.4.4 Predicted Annual Fuel Consumption of Electrically Coupled System

Figure 2.3.4.5 shows the annual fuel consumption versus average wind speed for the mechanically coupled system operating against the assumed load pattern. Fuel savings for the mechanically coupled system compared with the no VAWT case were predicted to be 10.7% for an average wind speed of 5.5 m/s (12.3 mph) and 21.5% for an average wind speed of 10 m/s (22.4 mph).

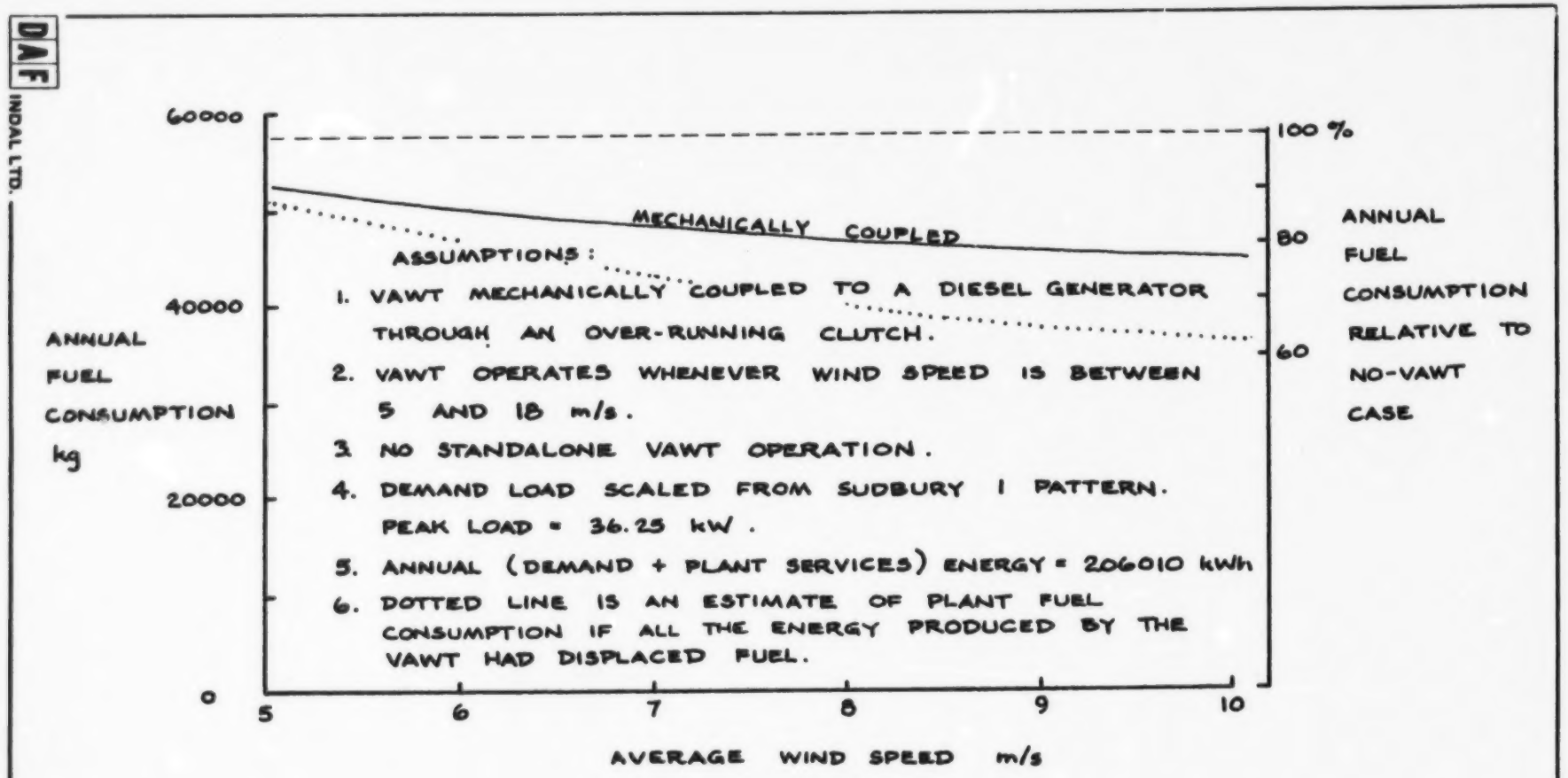

DAF
INDAL LTD.
60000
40000
20000
0
ANNUAL FUEL CONSUMPTION kg
100 %
80
60
ANNUAL FUEL CONSUMPTION RELATIVE TO NO-VAWT CASE
MECHANICALLY COUPLED
ASSUMPTIONS :
1. VAWT MECHANICALLY COUPLED TO A DIESEL GENERATOR THROUGH AN OVER-RUNNING CLUTCH.
2. VAWT OPERATES WHENEVER WIND SPEED IS BETWEEN 5 AND 18 m/s.
3. NO STANDALONE VAWT OPERATION.
4. DEMAND LOAD SCALED FROM SUDBURY 1 PATTERN. PEAK LOAD = 36.25 kW.
5. ANNUAL (DEMAND + PLANT SERVICES) ENERGY = 206010 kWh
6. DOTTED LINE IS AN ESTIMATE OF PLANT FUEL CONSUMPTION IF ALL THE ENERGY PRODUCED BY THE VAWT HAD DISPLACED FUEL.
5
6
7
8
9
10
AVERAGE WIND SPEED m/s

Figure 2.3.4.5 Predicted Annual Fuel Consumption of Mechanically Coupled System

3. SUDBURY II TASK 03 CONCLUSIONS & RECOMMENDATIONS

3.1 First Order Torsional Natural Frequency

The predicted first order torsional undamped natural frequency for the Sudbury II electrically coupled system lies approximately midway between the two per rev and three per rev VAWT rotor forcing frequencies. This improved prediction was made possible by measurement of electrical coupling stiffness (see Section 2.1.1). The remaining model stiffness values were previously measured. Model inertia values were either calculated or taken from manufacturers' data (Task 02 report).

3.2 Dump Load Reinforcement of the Three Per Rev Forcing Function During Electrically Coupled Operation

Installation of a notch filter in the dump load controller feedback loop, tuned to the three per rev forcing function, resulted in elimination of torque ripple at that frequency. The effect of the filter is to virtually eliminate dump load response at the notch frequency. Earlier suspicions that some aerodynamic abnormality of the rotor was causing the unusually strong three per rev response appear unjustified in light of these results.

The remaining two per rev forced response is normal for a two-bladed VAWT.

3.3 Recentering of the Seven Hz Notch Filter to Reduce Stand Alone Torque Excursions

The remaining seven Hz steady state torque ripple is believed to be within acceptable limits (see Section 2.1.3).

3.4 System Response to "Long Term" Changes in Load and Wind Speed

It is concluded that stand alone operation based on the present configuration would not be practical. The demand load that could be reliably supported is too small, relative to the VAWT rating (and hence cost). An excessively large number of diesel start/stop cycles would also result. It is recognized that an energy storage and recovery system is needed to average out the effects of wind speed fluctuations. (See Appendix B and report Sections 2.2 and 4.2.)

3.5 Fuel Savings

The fuel saving performance of the electrically coupled system is adversely affected by the dump load operations, which is necessary to maintain a minimum diesel engine load.

The fuel saving of the electrically coupled plant supplying an assumed demand load pattern, relative to a similar diesel plant without the VAWT was estimated to be 5.7% when the average wind speed was 5.5 m/s. The use of a short-term energy storage and recovery system would improve fuel consumption performance by reducing or eliminating the need for a dump load.

4. SUDBURY II PROJECT CONCLUSIONS AND RECOMMENDATIONS

4.1 Proof of Concept

The Sudbury II work has shown that a two-bladed Darrieus wind turbine can be controlled by load modulation with sufficient precision to synchronize it to an existing utility bus. This was demonstrated for wind speeds up to 24 mph.

It was further demonstrated that system frequency could be controlled within utility guidelines for both the wind turbine stand-alone case, and the electrically coupled case. For the electrically coupled case, utility guidelines for voltage excursions have been met with the existing system. Voltage excursions for the existing stand alone system fail to meet guidelines by a very narrow margin.

4.2 Short Term Energy Storage and Recovery

There is a need to address the problem of wind speed variability because it affects the ability of the stand alone wind turbine to consistently carry any given demand load (see Appendix B and Sections 3.4 and 2.2). This problem is addressed in the DAF Indal proposal document Sudbury III Short Term Energy Storage Demonstration, October 15, 1984 submitted to the Canadian Electrical Association.

Although the proposal does not entail system optimization, candidate energy exchange concepts will be reviewed for technical maturity and promise, potential for broad application, remote site reliability, ease of maintenance and cost effectiveness. Emphasis is expected to be placed on battery storage technology.

4.3 Speed Modulation by Solid State Load Control

It is concluded that solid state power handling devices based on wave chopping can be used to govern wind turbine speed.

4.4 Potential Fuel Savings

It is concluded that the electrically coupled wind/diesel hybrid is less effective in saving fuel than its mechanically coupled counterpart. In some applications, utilization of the fuel and wind energy could be improved by directing the dumped energy to a useful load. A short term energy storage and recovery system could also improve fuel savings.

APPENDIX A

Test Procedure for Measurement of Electrical Coupling Stiffness

Test Procedure for 11/30/84
Measurement of Electrical Coupling Stiffness

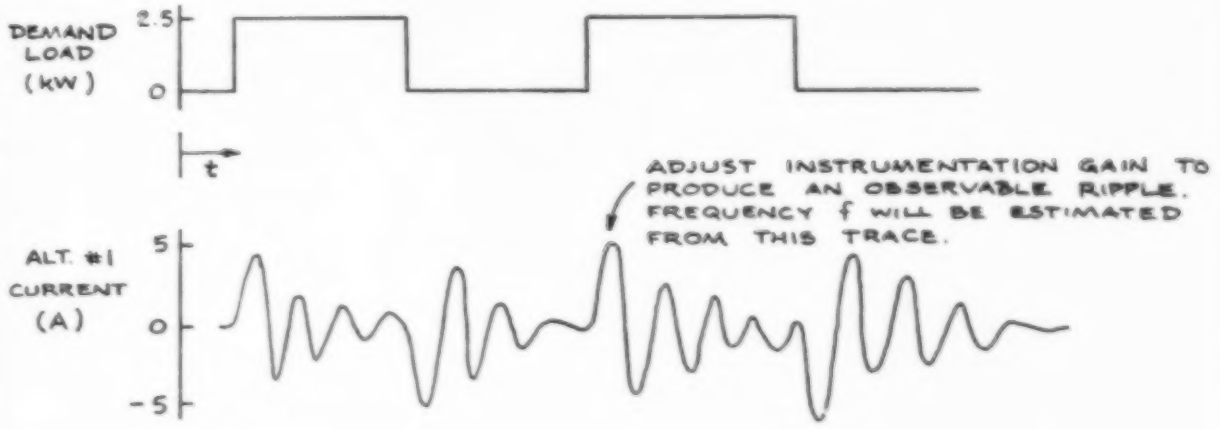
1. Start up system. Synchronize VAWT Alt. #1 to Diesel Alt. #2.

2. Reduce demand load to zero.

3. Stop VAWT but leave Alt. #1 electrically coupled to Alt. #2. (Alt. #1 is motoring, overrunning clutch is slipping.)

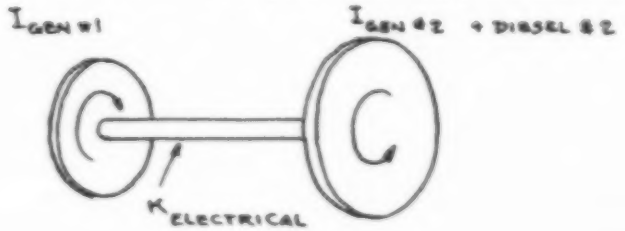
4. Take chart recording of Alt. #1 and/or Alt. #2 current at chart speed 25 mm/sec (approx).

5. While taking chart recordings, apply a small step load change using the demand load bank.



6. Return with chart records.

7. We will analyze data approximately as follows:



$$(2\pi f)^2 = K_{EL}\left(\frac{I_{G1} + I_{G2D2}}{I_{G1}\, I_{G2D2}}\right)$$

WHERE f IS THE MEASURED FREQUENCY IN HZ AND K_{EL} IS WHAT WE WANT TO FIND.

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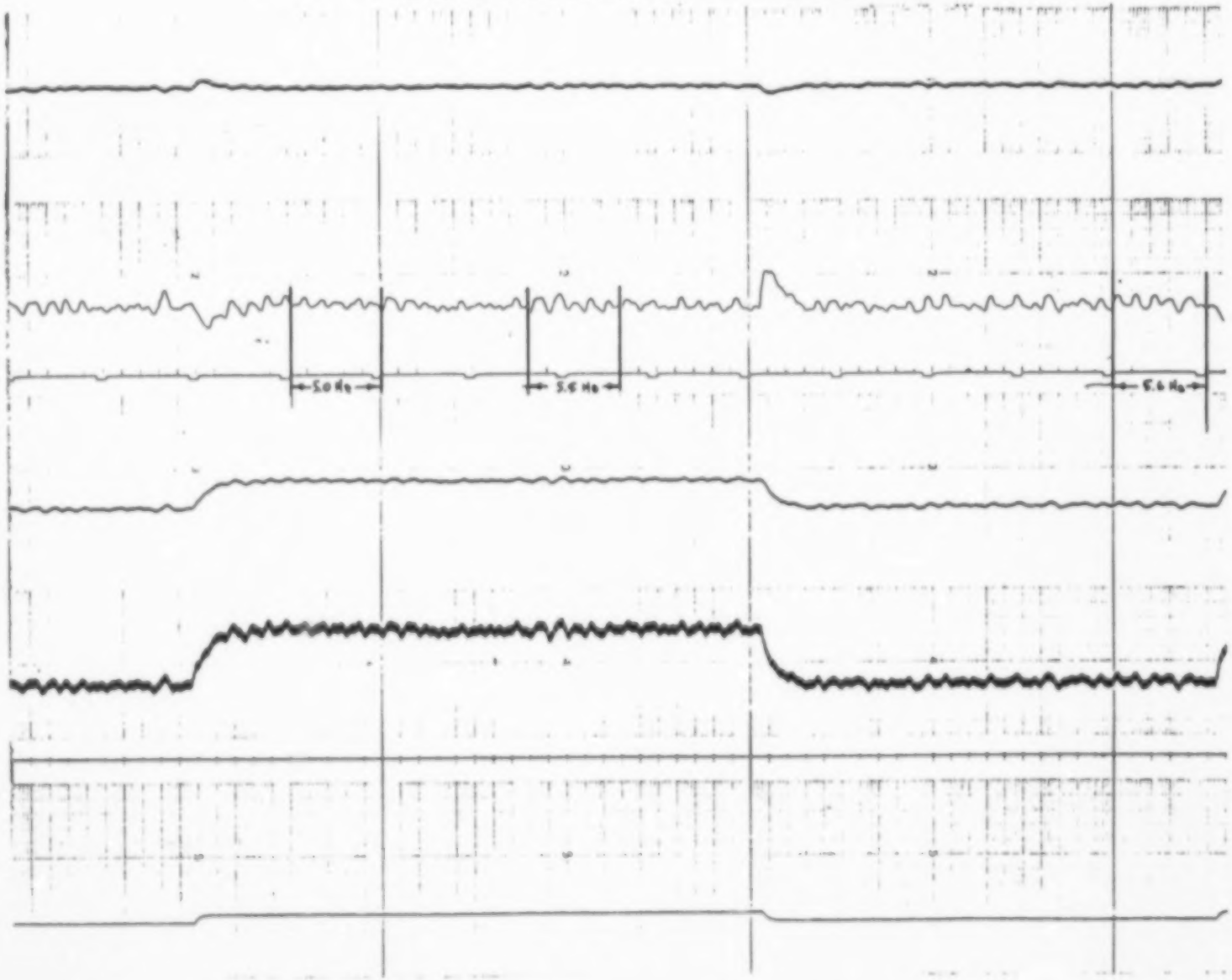
FIGURE A1 Results of Electrical Stiffness Test Dec. 6/84



APPENDIX B

Ontario Hydro Site Visit of Sept. 26, 1984

Mr. Hammett

September 28, 1984

File: 908-01662 P

SUDBURY WIND/DIESEL DEMONSTRATION

SITE VISIT SEPTEMBER 26, 1984

The Sudbury Wind/Diesel Site was visited by W. Moll and P. Drewes of Power Equipment as part of the requirements of Task II of the Extended Testing Program. Task II entails the development of a "wind alone" running capability for the wind/diesel power plant and the purpose of the site visit by Ontario Hydro engineers was to witness operation of the unit in this mode. Acceptable stand alone operation requires the system to be capable of maintaining frequency, synchronizing the wind turbine with the diesel generator and conversely synchronizing the diesel generator with the wind turbine. These three functions require the use of the dump load controller and must all be performed within given limits of voltage and torque excursions.

DAF Indal staff was at the site conducting fuel consumption tests under varying wind and load conditions. Wind speeds during the day ranged from approximately 10 mph to 30 mph and all modes of operation were demonstrated during that time. Strip chart recordings were made for typical operational modes. Strip chart recordings were also made for special events (manual shut down of wind turbine, sudden changes in demand load, etc.) to investigate the stiffness of various components and the occurrence of harmonics within the system.

As set up, the electrically coupled wind/diesel power plant as proposed in the Extended Testing Program operated successfully. The wind turbine will synchronize with the diesel generator and given sufficient wind, the diesel will shut down, leaving the wind component to supply total power. The diesel will then come back on line as wind speed decreases or the load increases. However, control of the wind turbine throughout all these operations is achieved by use of a dump load and the philosophy of this approach should be reviewed in light of the overall fuel savings achieved with this configuration and its impact on a practical operation of the diesel plant.

The goal of stand-alone capability is a direct result of the original Sudbury Wind/Diesel Demonstration Program. Data from this testing program revealed that fuel savings for a mechanically coupled wind diesel power plant were marginal as long as there was a requirement for full-time operation of the diesel component (the diesel governor was used to maintain system frequency). It was therefore felt that fuel economy could be greatly improved if the diesel component could be shut down when the wind component was capable of meeting the full demand load.

To run in a stand-alone mode, the response of the dump load was greatly improved by the installation of a solid-state controller. As demonstrated during the site visit, this unit has made stand-alone operation possible. However, the price of control may in fact be an impractical operating pattern for the diesel plant (too many stops and starts) resulting in an overall reduction in system efficiency as well as poor diesel reliability and shortened life. This point may be best illustrated by reviewing the various parameters for the September 26th run.

Qualitatively the afternoon could be described as fairly windy. Speeds ranged from 10 to 30 mph. The important factor however is the gustiness of the wind. It appeared to blow in 2 to 3 minute 25-30 mph cycles followed by 6 to 7 minute 10-15 mph cycles. As presently configured, the dump load is capable of dissipating 32 kW of power.

The system will operate satisfactorily in a parallel situation, that is, a relatively large demand where the wind contribution simply reduces the output from the diesel generator. The dump load rarely operates and little energy is wasted. To assess stand-alone capability, the demand load was reduced to the point where the diesel unit shut down. Under the above mentioned wind conditions, this demand was 5 kW. This is a very low demand considering the average output of the wind turbine. The dump load is working overtime and dumped energy far exceeds useful demand energy. Figure 1 illustrates the energy pattern for the stand-alone operation.

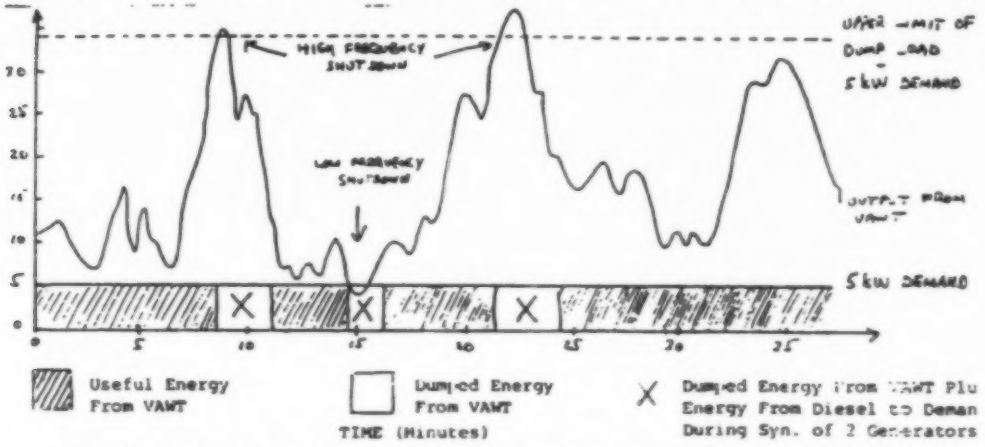


Figure 1

Even with a low 5 kW demand, the system required one automatic diesel start-up when the wind suddenly dropped to a 10 mph range resulting in a low speed shut down. The system is fully capable of this task but it requires a full transfer of demand load to the diesel during synchronization, thus sacrificing fuel economy.

The system also experienced several high speed shut downs. These again result in a transfer of power to the diesel and require much longer time for re-synchronization of the wind turbine because of highwinds. While high speed shut downs can be eliminated simply by increasing the range of the dump load above 32 kW, they are an indication of the energy being wasted in the dump load resistance. Qualitatively it appeared that two or three times the actual demand energy was dumped by the controller on Spetember 26. Although energy dumped in excess of demand load is itself not a problem, there are two serious implications for the observed operation which should be of concern. These are that for a typically small remote community, the wind turbine would have to be very large relative to the minimum load to permit stand-alone operation and the dump load bank would need to be sized to the full capacity output of the wind turbine. For Fort Severn with 50 kW minimum load, the wind

turbine and dump load would need to be in the order of 350 kW; not practical or cost effective. Clearly some form of short term active storage buffer will be needed to make stand-alone operation practical.

In summary, DAF Indal Ltd. has demonstrated the capability of the stand-alone control system. The usefulness of stand-alone capability is limited, not by any technical factors, but simply by the inherent gustiness of the wind. Modellers, predicting the performance of wind turbines should give careful consideration not only to the annual wind speed distribution curves for a given location, but more importantly to the duration of these wind speeds. Unless the dumped energy can be recovered in some useful form, stand-alone operation using a dump load controller does not appear practical.

Conclusions

1. Stand-alone operation in the present configuration would require a substantially oversized VAWT to meet community demands - not practical.

2. Depending on VAWT size, the stand-alone configuration would still result in increased cycling of the diesel generator - potentially damaging to diesel reliability and maintenance schedule.

3. The inherent gustiness of the wind suggest that a two way exchange of energy between supply and storage is required. (The use of batteries for this purpose may be limited not by the kWh capacity, but by the charging and discharging rates required).

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